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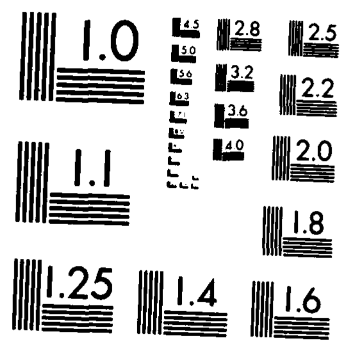

MICROCOPY RESOLUTION TEST CHART
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NUCLEAR HARDNESS MANAGEMENT

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Technical Report

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An ap roach to formalizing nuclear hardness validation for electronic equipments is presented. It uses margins, defined methods, standards and formalized rules for constructing the simplest validation methodology from available methods.

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INTRODUCTION AND SUMMARY

1.1 OBJECTIVE.

Nuclear Hardness Management is currently the principle bottleneck in achieving, with confidence, reasonable levels of nuclear hardness in tactical electronic system. Techniques and devices exist whereby electronic systems can be hardened to accepted tactical nuclear levels (i.e. those up to the level of immediate personnel incapacitation). The means whereby these methods can be applied at reasonable cost to achieve the needed hardness are in question. The option of elaborate test and analysis programs, including independent hardness audits and realistic stress exposures followed by extensive hardness maintenance and surveillance efforts, is not reasonable for tactical systems. The current practice of using expert government consultants to advise program managers on a minimum set of hardening and hardness validation efforts is a reasonable near-term expedient, but a more objective method must be developed for the long term.

This report establishes the basis for a formal and objective Nuclear Hardness Management methodology. It is based on the following premises:

1. The ingredients of nuclear hardness management should be as similar as possible to the methods used to manage other environmental stresses and degrading effects (e.g. Reliability), with which the managers and engineers are already familiar.

2. The rules for applying nuclear effects data and for demonstrating that the nuclear hardness requirements have been achieved must be part of the contract package during the competitive phases of procurement.

3. Uncertainties in data, analyses, test results, and extrapolation to realistic conditions are compensated by demonstrated margins. The magnitudes of these margins are legislated by the government, based on the best available technical data.

4. The design and test organizations are provided as much freedom of choice as possible to allow them to trade off hardness related requirements against all the other system requirements. Only if some design choices are inherently unhardenable or incapable of hardness validation with any reasonable margin are they proscribed.

5. While the design and test organizations are provided the choice, these choices will be biased because some design and validation options will require larger safety margins or incur more cost in implementation.

By analogy with other "-ilities", the implementation of Nuclear Hardness Management should occur through various documents that provide direction and guidance to the participants in system development and validation programs. At the apex of this document tree is the existing DoDI 4245.4, which directs that nuclear survivability (for which nuclear hardness is one contributing factor) will be considered by the DSARC for all major DoD systems, and will be considered by the Service acquisition review councils for other systems. DoDI 4245.4 also spells out the authority and responsibility of various organizations for establishing the requirements, assuring that they have been met, and reviewing the overall program. Other existing documents include each Service's regulation (i.e. AR 70-60, OPNAVINST 3401.3, AFR 80-38) that define the procedures whereby the nuclear hardness requirements are formulated for new systems developed by that service. Each Service has established organizations (e.g. the Army's Nuclear Survivability Committee and its Secretariat) to implement these procedures.

What is now needed is to carry this process much further. Having established the machinery to formulate nuclear hardness criteria in environmental form (i.e. the environment to which the system may be exposed without unacceptable response), it is now necessary to write down the rules by which it will be judged that the criteria have been satisfied, and to provide to the development organizations the tools by which they have reasonable expectation of achieving success according to these rules. This is not an easy task: a lot of documents are needed and the technical decisions that underly these rules will stress our understanding of the nuclear effects phenomenology to its limits. The potential impact will, however, far outweigh the cost. Even the impact of cutting down on the incessant arguments about, "Is it hard or not?" will save a lot of money and time.

1.2 RECOMMENDATIONS.

It is the recommendation of this report that a variety of documents be prepared, to supplement the technical reports already provided by DNA, each to meet a specific need. These documents should be of two major classes:

1. Directive documents that can be cited in contracts and carry the force of law/authority. These documents must be specific and pragmatic: ideally they should leave no question whether a program has or has not complied with their requirements. These present the rules of Nuclear Hardness Management. These rules are mandatory, subject to specified procedures for granting waivers.

2. Advisory documents that are offered to the system development community to help them accomplish the design and testing in compliance with the Directed rules. Such documents are useful, but not mandatory.

Within the class of Directive documents, there are the following types:

1. Management documents, which define responsibilities, procedures and authority (e.g. DoDI 4245.4 and related Service documents). Such documents insert activities related to nuclear hardness into the normal flow of acquisition management at all levels. As discussed above, such documents already exist at the highest level; the need is to flow down the requirements at lower management levels, probably by amending existing documents to insert nuclear-hardness specific requirements.

2. Hardness Validation Methodology documents, which define the rules whereby an acceptable hardness validation methodology can be developed for each specific system. This methodology will usually be a set of individual methods (e.g. analyses and tests) from which data is provided to a survivability assessment (i.e. prediction of system response to realistic operational conditions). As discussed above, the Hardness Validation Methodology documents will provide as much flexibility of choice of individual methods as possible, subject to legislated completeness criteria and required margins, so that each system manager can choose the specific methodology that's most appropriate to his design.

3. Specification formats, which identify all the data required for an item specification to be complete enough to satisfy hardness and hardness validation requirements. Specific item specifications (e.g. with specific values for parameters) need to be prepared by the system development organization. However, in order to implement hardness validation it's necessary to ensure that at each level (i.e. from the prime item down to the elementary device or piece part) the specifications satisfy minimum completeness conditions.

4. Standards, which establish minimum conditions to be met for any method used in the Hardness Validation Methodology. These include standards for tests (i.e. each test type should reference a Standard that ensures that any competent test organization performing the same test will measure in essential attributes the same response), and for analyses. This does not imply that a particular computer code is specified by the Standard, only that any acceptable code has to meet specified minimum conditions (possibly including validation by specified test problems).

5. Certified Data, which provide to the development organizations data and relationships that are accepted by the government as being valid without further need for justification. While such documents are not essential to the management approach being recommended, they can save much unnecessary and duplicative effort in applying the validation methods.

Examples of useful (but not contractually binding) documents are:

1. Tutorials to explain the nuclear weapons phenomena at various levels of sophistication for various audiences. These can be at the level required by persons training to become nuclear effects experts, they can serve as a handbook of existing knowledge (e.g. EM-1), and they can provide general insight to aid the person who has no need to become a nuclear-effects specialist (e.g. design engineer) to gain sufficient insight to perform his function.

2. Guideline documents to assist in the application of the various mandatory documents. For example, the Specification formats can be supported by a guideline by which the engineer can be aided in determining the values to be inserted into the specifications. Similarly, there are guidelines for the designers and test engineers, which assist them in making the decisions and in interpreting the results. These documents are separate from the Standards that impose legalistic constraints. The engineers are free to choose different methods from those recommended in the Guidelines. They are not allowed to violate the limits on acceptability imposed by the Standards. This is one reason for presenting the Standards and Guidelines as separate documents: it avoids confusion over what is mandatory and what is discretionary.

3. Data bases, which present results of previous tests and analyses. These are useful for the design and test organizations, but they are distinct from the Certified Data in that the user has the responsibility to demonstrate the validity and applicability of the data (presumably by criteria imposed by the Standards).

4. Technical Background documents, which establish the technical foundation for the formal Methodology and Standards documents. For each recipe presented in the mandatory documents, a Technical Background document should present a technical audit trail, including the assumptions on which the recipe is based and the evidence that appears to support (or contradict) the assumptions. These documents are intended primarily for the nuclear effects specialists, rather than the applications engineers. They are essential counterparts to the formal recipes, especially to facilitate dealing with changes in understanding and threats. Technical uncertainties underlying the rules must be documented to facilitate an ongoing expert review of the validity of the rules, but the discussions about uncertainties should not distract from the legalistic nature of the rules.

The principal features of the recommendations of this report are illustrated by the foregoing examples and discussion:

1. There is a clear distinction between government mandated procedures for validating the nuclear hardness of equipment and the technical rationale (and risk) underlying those procedures. The government accepts the risk of the procedures being inadequate; the developer accepts the risk of the equipment not complying with the requirements imposed by the procedures.

2. Where there are uncertainties, they are compensated by margins. Again the margins are mandated, with the government accepting the risk of insufficiency in the mandate.

3. Within the bounds of adequacy defined by the Methodology, Standards and Specifications, the development organization should be provided with the greatest possible freedom to perform design and validation tradeoffs taking into account all factors, including hardness considerations.

1.3 QUESTIONS.

The key questions that may need to be answered before DNA can decide to proceed to develop the required documents are:

1. Is there a need?

2. Will this approach satisfy the need?
   a. Is it technically feasible?
   b. Is it practical?
   c. Are system developers likely to accept it?

3. Is the expected benefit consistent with the required investment?

Is There a Need?

It appears clear that a need for a better formalism for judging the adequacy of nuclear hardening military systems, especially electronic systems, is clearly established by past and recent experience. While some systems programs have considerably improved their interactions with the nuclear effects technology community, making increased use of nuclear effects expertise to influence the designs of the system, their continues to be a dichotomy between the opinions and advice of nuclear effects experts and what is actually implemented in hardware, and in the extent of nuclear hardness validation test programs. There is even considerable disagreement between the experts on the "how much hardening is enough." This disagreement is justification for programs doing less than some of the nuclear effects expert advise; if the experts can't agree amoung themselves, a program manager cannot be criticized for exercising his own best judgement on the extent to which he should devote the taxpayers' money to nuclear hardening and hardness validation tasks. It appears clear that the new DoD instruction, DoDI 4245.4 will not lead to an increase in attention to nuclear hardening unless there are reasonably clear criteria for success by which the program management and execution can be judged. It is unlikely that the ATSD/AE will be able to persuade the DSARC to disapprove a program just because he or some nuclear effects consultants don't believe that nuclear hardening was carried out thoroughly enough. If there were a reasonable standard for acceptable hardening and hardness validation, such disapproval could be based upon evidence that the standard was not heeded in the course of that program. We submit, therefore, that past and present experience clearly establish that there is a need for an agreed upon formalism by which adequacy can be judged.

Will the recommended approach satisfy the need?

There are three aspects of this question that are closely interrelated:

a. Is it technically feasible?

b. Is it practical?

c. Are system developers likely to accept it?

Taking them in inverse order, it's asserted that if the procedures are both feasible, practical, and enforceable system developers will comply with them. The fundamental rule of system development is to minimize risk. One element of risk is that the program will be held up at the DSARC for lack of satisfactory hardness validation. This risk is minimized if a pre-established set of rules has been followed, assuming that there are no other severe penalties for following the rules.

That raises the key question of practicality, which can be quantified in terms of the penalties (e.g. cost, schedule, performance) that have to be absorbed to deal with hardness according to the prescribed rules. If these penalties are severe, they are difficult to comply with. Where the penalties are negligible the designers have always been willing to incorporate hardness features. It's in the middle ground where tradeoffs have to be made between hardness features and other system parameters that objective rules are needed that will produce reasonable results. Many system organizations have already performed these tradeoffs and have incorporated many hardening features as a result. The key question is whether the results are technically adequate.

Thus, the question of technical feasibility is not one of principle, but one of practicality. Is it possible to prescribe an objective method of hardness validation that satisfies technical adequacy requirements without imposing unrealistic burdens on the system design and testing? One argument against this possibility notes that the ability to analyze a nuclear effects response is limited by the number of parameters that even our most sophisticated computer codes can handle. In practice these analyses impose obvious simplifications on what are very complex objects. At present these simplifications are the result of individual analyst's judgements. Each analyst tends to make them somewhat differently. How can one ever write an objective prescription for reducing a complicated geometrical and electrical configuration to the parameter space available in the computational tools?

The answer to this doubt comes from taking a fundamentally different point of view: the purpose of a hardness validation analysis is not to make the best estimate of the expected response of a system to a nuclear-induced stress, but to establish a bound on the response that falls within the range of acceptable behavior. This approach opens up new avenues of practicality and tradeoffs between margins and sophistication of validation methods. It also establishes the basis for a contractual formality: the margin needed to compensate for uncertainties in various methods can be officially defined and contractually imposed. This presents the developer with the ideal risk-minimizing approach: he is held blameless as long as he follows the prescribed rules. The government accepts the risk that the rules are later found to be inadequate.

There is still a last question: is there a reasonable amount of design space available for incorporating enough margin to make up for the uncertainties in hardness validation methods? We believe there is, as witnessed by the fact that this procedure is commonly used to deal with most nuclear effects design issues. On many occasions developers have argued that certain tests weren't necessary because a large margin was incorporated into the design, and those arguments have frequently been persuasive. In those cases it should be possible to formulate criteria by which the conclusion can be endorsed. Furthermore, we believe there are many other circumstances under which other waivers from nuclear effects tests could have been granted, but they were not requested because the tests were relatively painless to the developer. In some cases, the same programs were criticized for not addressing another issue, for which no money was available. Clearly, saving money from unnecessary tests is worthwhile when there are more critical issues to which these resources could be directed.

Is the Benefit Consistent with the Investment?

A sizeable investment in talent and money will be required to implement our recommendations. Translating the existing knowledge into recipes applicable to a wide range of circumstances is technically challenging, and requires a discipline that is difficult for most technical people to learn. It's expected that the price tag will be a few million dollars spread over a few years, together with a need for tight management control to ensure that the discipline is maintained (i.e. avoid converting these resources into funds for technical hobby shops). We believe the payback to the nation will be many times the investment, as it has been in every other engineering area when it has become a formalized discipline. Individual decisions relating to hardness validation for single systems have a price tag comparable to this investment. It's likely that the effect of this discipline on the hardness of one major military system will pay back the total cost. Even the cost of arguing about hardness, as accumulated over many systems, is comparable to the investment.

1.4 ORGANIZATION OF REPORT.

The remainder of this report will discuss in more detail these issues, illustrating them to make credible the practicality of this approach. In Section 2 we will address some general features, including the role of various documents, a hierarchical approach to analysis/testing, and the impact of statistical considerations. In Section 3 we will present in annotated outline form an electronics hardness validation methodology applicable to Army tactical systems, including a catalog of documents needed to support it. More detailed outlines of some of the documents are included in Appendices.

SECTION 2
PARTICULAR ISSUES

2.1 INTRODUCTION.

In this report we take the point of view that achieving hardness with reasonable confidence requires that the technology of hardening be developed into a mature engineering discipline. The interrelated ingredients of such a discipline are:

1. Means to specify contractually in pragmatic terms what is required i.e., what data are required, by what rules are the data related to system hardness, how does the manufacturer demonstrate compliance with hardness required?. This applies to the system and to all lower levels of assembly down to the piece-part.

2. Quantitative information by which to perform design trade-offs (e.g., parametric interrelations between hardness achievements and other factors, such as performance, weight, cost, etc.).

3. Calculational and experimental tools needed to perform the design trade-offs (e.g., numerical and experimental simulation).

4. Documentation of these techniques and data in textbooks, handbooks, design guidelines, specifications and standards so that design and evaluation engineers can learn to use them, in effect incorporating them as an integral part of the design process.

5. Procedures for design review, equipment qualification, and unit acceptance.

The analog to reliability engineering is particularly instructive. The prime item specification generally includes minimum reliability requirements (e.g., Mean Time Between Failure) and may also prescribe some of the results whereby the design is to be accomplished (e.g., factors for accelerated testing of devices on which adequate statistical data are unavailable; proscription against the use of certain designs). A review procedure may be required, including a review board in which a representative of the customer and his expert consultants participate.

The prime item designer then allocates the reliability budget among the various subsystems. The same procedure is followed to translate the subsystem requirements into pragmatic procedures applied to the design and qualification of each subsystem, and so forth down to elementary parts and materials.

Of course the practice is not as complete as implied above. Experience has taught that many features are not critical for reliability and can be dealt with casually. Others are recognized to be critical, frequently because of the unsatisfactory experience in some other applications. Reliability is a strong force for conservative design: promoting the use of materials and devices that have demonstrated reliability. New technologies offer the promise of increased capability, but usually at some risk of introducing a new (usually unexpected) failure mode.

Important tools for reliability and engineering include:

1. Previous design experience, including the resulting data base.

2. Standards and specifications: ways of doing things that are reasonably invariant to who is doing them.

3. Accelerated testing: means of establishing acceptable long-term performance by short term overstressing (either for lot quality sampling or nondestructive screens).

4. Nondestructive and destructive testing (screen or sampling).

5. Independent reliability audits by a quality control staff separate from design staff.

6. Appropriate and defined procedures for statistical treatment of data.

As a result of applying these tools, the system is designed so that adequate performance is maintained in spite of the inevitable parameter variations. Reliability critical items are flagged for particular attention, including special quality control measures when needed.

By comparison, hardening technologies have not achieved the status of a mature engineering discipline. A large body of knowledge exists. Experts can recommend design practices that are likely to harden a system, but rarely is the information suitable for quantitative judgement in trade-offs between hardness and opposing factors. As a result most system hardening efforts have concentrated on obvious problems and on solutions that made relatively little negative impact otherwise. The hardness of the end product is debatable: the designers point to the hardening features; the critics point to the remaining uncertainties; the designers retort by accusing the critics of promoting their own hobby; etc.

This report outlines the makeup of a future engineering discipline for hardening tactical ground systems to the stresses produced by nuclear radiation and nuclear EMP exposure. The methodology as described, is based on existing knowledge extrapolated by judgement.

The approach taken is that the experts knowledge should be translated into codified procedures (i.e., recipes) to be applied by the SPO, designers and vendors. In particular, uncertainties (due to lack of knowledge, complexity, statistical variations, etc.) should be reflected in prescribed design margins or, equivalently, methods to establish worst case limits and relevant tests. This approach does not exclude rules that prohibit some designs (either specifically or by imposing unacceptable design margins). We believe however that the hardening technologists should not try to legislate what designs should be used; their lack of expertise in the many factors not related to hardness is likely to lead to faulty design, or a nonoptimal one. If it is necessary to proscribe a design concept because it is inherently impossible to maintain or establish its hardness, so be it. But we must leave the designers as much room in the multi-parameter design space as possible. This situation too has its analog in non-nuclear reliability.

There is a legitimate concern over a serious asymmetry between normal reliability and nuclear reliability: most but not all normal reliability weaknesses come to light during peacetime operation and testing. Nuclear reliability test programs are not likely to become as extensive and realistic as missile test flights. While most items will be exposed to a wide range of non-nuclear stresses (e.g., acceleration, vibration, vacuum) both during testing and operation, the specified nuclear environment is a worst case envelope to which only a small fraction of the force is likely to be exposed. These factors must be weighed seriously in establishing discipline. In general this situation should produce more conservative designs (i.e. larger design margins) to compensate for less realistic testing for nuclear as compared to non-nuclear reliability.

The remainder of this Section will develop this view in more detail. In Section 2.2 we will use a particular example of a procurement specification to illustrate the existing controls on the Reliability program and other -ilities, and point out the comparative lack of maturity in references to Hardness Management procedures. Section 2.3 will discuss in more detail the definitions and characteristics of various documents that need to be prepared to support the recommended Hardness Management procedures. Section 2.4 will address one of the critical issues: how to deal with variations and other uncertainties. Section 2.5 develops in more general form the tradeoffs available to the development organization resulting from a hierarchial structure of analysis and test methods. Section 2.6 describes a tool that aids in simplifying the hardness assessment problem: the zone concept. Finally, Section 2.7 describes the impact of margins on hardness assurance, maintenance, and surveillance.

2.2 PROCUREMENT PROCESS.

Hardness Management will be more efficient and more easily accepted by developers if the techniques follow as closely as possible those already applied in other areas, with which the managers and engineers are already familiar. It is instructive, therefore, to review the kind of documents that are commonly used in procuring, designing and testing electronic hardware, irrespective of nuclear effects requirements.

Whether an item to be developed is a major system (e.g. missile) or a small part of a system (e.g. electronic device or module) the necessary characteristics of the item are defined in a Procurement Specification. In principle, this document defines in a legally enforceable manner those capabilities and environmental tolerances that the item must have to be acceptable. Part of the specification deals with the specific capabilities required to perform the mission (e.g. the range/payload and CEP of the missile, the gain and stability of an amplifier). Another part establishes the means by which these capabilities must be demonstrated (e.g. the number of test flights and associated success rate, the test methods and environmental variables for the amplifier gain measurements). Another part addresses a large number of auxiliary issues that are normally overlooked by scientists, but represent the backbone of system engineering. These are usually covered by reference to a long list of government documents (e.g. MIL-STD's and others) that prescribe how things are to be done, and sometimes proscribe some options.

2.2.1 Reliability Example.

This point can best be illustrated by reference to a specific procurement specification, one prepared by Westinghouse Electric Corporation to procure an Output Device for Airborne Radio Receiver Miniature Receive Terminal (MRT). In this case the specification covered an item to be furnished by a subcontractor to Westinghouse, who would incorporate it into the Airborne Radio Receiver for delivery to the Government. Sections of this Specification will now be used to illustrate the procurement process. This Specification is typical of specifications at all levels of assembly. As a matter of fact, it can be safely assumed that many of the entries in this Specification are simply copied from the higher level specifications levied on Westinghouse by the Government.

The Table of Contents for the Specification is shown in Figure 1. Normally, our attention would focus on Section 3, which appears to contain the meat of the matter: what is the item supposed to do. However, a major input comes from Section 2, Applicable Documents. This section is reproduced in Figure 2. It consists of 7 pages of document titles, each of which comprise many pages. Yet the beginning of Section 2.1 states," The following documents ------- form a part of this specification -----". While it is tempting to discard this as so much bureaucratic red tape, the contractor who does so is flirting with insolvency. Most of these documents are not to

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Figure 1. Table of contents, Westinghouse Specification No. 645A094.

Specification No. 645A094
Date: 1 March 1985

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Figure 1. Table of contents, Westinghouse Specification No. 645A094 (continued).

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Figure 1. Table of contents, Westinghouse Specification No. 645A094 (continued).

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Figure 1. Table of contents, Westinghouse Specification No. 645A094 (concluded).

1 O SCOPE.

1.1 Item Description. This specification establishes the performance, design, development, and test requirements for the Output Device for the Miniature Receive Terminal (MRT) herein referred to as the Printer.

2.0 APPLICABLE DOCUMENTS.

2.1 Government Documents. The following documents of the exact issue shown form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.

SPECIFICATIONS:

Military

MIL-G-3056D	Gasoline, Automative, Combat	29 Sep 1975
Amendment 2		5 Jul 1979
MIL-B-5087B	Bonding, Electrical, and Lighting Protection, for Aerospace Systems	31 Aug 1970
Amendment 2		12 Jul 1977
MIL-E-5400T	Electronic Equipment, Airborne, General Specification for	16 Nov 1979
Amendment 1		5 Sep 1980
MIL-H-5606E	Hydraulic Fluid, Petroleum Base, Aircraft Missile and Ordnance	29 May 1980
Amendment 1		2 Mar 1984

Figure 2. Referenced specifications no. 645A094.

MIL-T-5624L	Turbine Fuel, Aviation, JP4 and JP5	18 May 1979
Amendment 2		10 Aug 1983
MIL-E-6051D	Electromagnetic Compatibility Requirements Systems	7 Sep 1967
Amendment 1		5 Jul 1968
MIL-F-7179E	Finishes and Coatings: Protection of Aerospace Weapons Systems, Structures and Parts, General Specification for	15 Nov 1972
Amendment 1		19 Sep 1974
MIL-L-7808J	Lubricating Oil, Aircraft Turbine Engine Synthetic Base	11 May 1982
MIL-B-7883B	Brazing of Steels, Copper, Copper Alloys, Nickel Alloys, Aluminum and Aluminum Alloys	20 Feb 1968
MIL-S-8516E	Sealing Compound, Polysulfide Rubber, Electronic Connectors and Electric Systems, Chemically Cured	30 Jul 1971
Amendment 2		29 Sep 1972
MIL-P-9024G	Packaging, Materials Handline and Transportability, System & System Segments; General Specification for	6 Jun 1972
MIL-P-13949F	Plastic Sheet, Laminated, Metal Clad, (For Printed Wiring) General Specification for	5 Dec 1977
Supplement 1		10 Mar 1981
Amendment 3		24 Apr 1984
MIL-F-14256D	Flux, Soldering, Liquid (Rosin Base)	17 Apr 1972
Amendment 2		21 Jan 1980
MIL-S-19500G	Semiconductor Device, General Specification for	16 Feb 1984
MIL-S-23586D	Sealing Compound, Electrical Silicone Rubber, Accelerator Required	29 Dec 1981

Figure 2. Referenced specifications no. 645A094 (continued).

MIL-S-25047C	Marking and Exterior Finish Colors for Airplanes, Airplane Parts and Missiles	18 Jun 1968
Amendment 1		12 Nov 1968
MIL-C-38999H	Connector, Electrical, Circular Miniature, High Density, Quick Disconnect (Bayonet, Threaded, and Breech Coupling), Environment Resistant, Removable Crimp and Hermetic Solder Contacts, General Specification for	27 Feb 1981
Supplement 1		21 Sep 1981
Amendment 1		15 Jun 1984
MIL-I-45208	Inspection System Requirements	16 Dec 1963
Amendment 1		24 Jul 1981
MIL-H-46855B	Human Engineering Requirements for Military Systems, Equipment and Facilities	31 Jan 1979
Amendment 1		5 Apr 1982
MIL-E-47220A	Coolant Fluid, Dielectric	29 Dec 1979
MIL-P-55110	Printed Wiring Boards	18 Jul 1978
Amendment 5		28 Mar 1984
MIL-C-55543A	Cable, Electrical, Flat Multiconductor, Flexible, Unshielded	6 Oct 1971
Notice 1		4 Apr 1983
MIL-P-55617B	Plastic Sheet, Thin Laminate, Copper Clad (For Printed Wiring, Primary or Multilayer)	10 Sep 1976
Amendment 1		3 Jun 1977
MIL-G-55636D	Glass Cloth, Resin Preimpregnated	25 May 1978
MIL-I-81550C	Insulating Compound, Electrical, Embedding Reversion Resistant Silicone	14 Jul 1983
MIL-P-81728A	Plating, Tin Lead (Electrodeposited)	27 Dec 1977
Amendment 1		28 Mar 1980
MIL-C-83286B	Coating, Urethane, Aliphatic, Isocyanate for Airplane Applications	18 Jun 1975
Amendment 2		19 Aug 1980

Figure 2. Referenced specifications no. 645A094 (continued).

MIL-C-83723D	Connector, Electrical, (Circular, Environmental Resisting), Receptables and Plugs, General Specification for	27 Dec 1977
Supplement 1		27 Dec 1977
MIL-C-83733B	Connector, Electrical, Miniature Rectangular Type, Rack to Panel, Environment Resisting, 200 Deg. C Total Continuous Operating Temperature, General Specification for	10 Dec 1980
Amendment 1		29 Mar 1980
Supplement 1		10 Dec 1980

Other Government Activity

DOD-D-1000B	Drawings, Engineering & Associated Lists	28 Oct 1977
Amendment 1		30 Nov 1978
ESD-616A-84-1	System Specification For Airborne Radio Receiver Miniature Receive Terminal (MRT) AN/ARR-XXX	11 Jan 1985
NSA 68-8E	NSA Specification For Rigid Multi-layer Printed Circuit Boards (Plated through Holes)	21 Dec 1978

STANDARDS:

Federal

Fed-STD-595A	Color	2 Jan 1968
Notice 8		30 Aug 1984

Military

MIL-STD-129H	Marking for Shipment and Storage	3 Jan 1978
Notice 4		30 Sep 1982
MIL-STD-130F	Identification Marking of US Military Property	21 May 1982
Notice 1		2 Jul 1984
MIL-STD-143B	Standards and Specifications, Order of Precedence for the Selection of	12 Nov 1969
MIL-STD-188C	Military Communication System Technical Standards	24 Nov 1969
Notice 1		1 Jun 1976
Notice 2		12 Nov
1976		

Figure 2. Referenced specifications no. 645A094 (continued).

MIL-STD-202F	Test Methods for Electrical and Electronic Components Parts	1 Apr 1980
Notice 5		28 Mar 1984
MIL-STD-275	Printed Wiring For Electronic Equipment	26 Apr 1978
Notice 5		7 Feb 1984
MIL-STD-454J	Standard General Requirements for Electronic Equipment	30 Apr 1984
Notice 1		30 Aug 1984
MIL-STD-461B	Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference	1 Apr 1980
MIL-STD-462	Electromagnetic Interference Characteristics	31 Jul 1977
Notice 4		1 Apr 1980
MIL-STD-704D	Aircraft Electric Power Characteristics	30 Sep 1980
MIL-STD-756B	Reliability Modeling and Predictions	18 Nov 1981
Notice 1		31 Aug 1982
MIL-STD-785B	Reliability Program for Systems Equipment Development & Production	15 Sep 1980
MIL-STD-794E	Part and Equipment, Procedures for Packaging and Packing of	15 Oct 1981
MIL-STD-810D	Environmental Test Methods	19 Jul 1983
MIL-STD-883D	Test Methods and Procedures for Microelectronics	31 Aug 1977
Notice 1		21 Jul 1978
MIL-STD-1388-1A	Logistic Support Analysis	11 Apr 1983
MIL-STD-1472C	Human Engineering Design Criteria for Military Systems, Equipment and Facilities	2 May 1981
Notice 2		10 May 1978

Figure 2. Referenced specifications no. 645A094 (continued).

OTHER PUBLICATIONS:

Handbooks

Military

MIL-HDBK-5D	Metallic Materials and Elements for Aerospace Vehicle Structures	1 Jun 1983
Notice 1		1 Jun 1984
MIL-HDBK-217D	Reliability Prediction of Electronic Equipment	15 Jan 1982
Notice 1		13 Jun 1983

Other Government Handbooks

DOD-HDBK-263	Electrostatic Discharge Control Handbook for Protection of Electrical and Electronic Parts, Assemblies and Equipment	2 May 1980

Other Government Documents

AFWL-TR-76-147	Nuclear Hardness Assurance Guidelines for systems with Moderate Requirements	Sep 1976
DI-E-7028A	Nonstandard Part Approval Requests/Proposed Additions to an Approved Program Parts Selection List	4 Mar 1981
DI-E-7031T	Drawings, Engineering and Associated Lists	
DOD-5000.39	Acquisition and Management Integrated Logistics Support for Systems and Equipment	17 Jan 1980
ESD-TR-83-197	Derated application of Parts for ESD Systems Development	Sep 1983
NACSIM 5100A	Compromising Emanations Laboratory Test Standard Electromagnetics (Secret)	1 Jul 1981
NACSIM 5203	Red & Black Engineering and Installation Criterions	30 Jun 1982
RADC-TR-75-22	Reliability Notebook	Jan 1975

Figure 2. Referenced specifications no. 645A094 (continued).

2.2 Non-Government Documents. The following documents of the exact issue shown form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.

SPECIFICATIONS

43999 GS 2569A03A	Long Range Combat Aircraft Vibration, Acoustic Noise Shock, and Acceleration Criteria	23 Nov 1981
43999 GS 2569A04B	Long Range Combat Aircraft, General Specification for Survivability/Vulnerability (Secret)	20 Dec 1982
Appendices		25 Jun 1984
43999 GS 2569A05B	Long Range Combat Aircraft Thermodynamic Environment	24 Feb 1983

3.0 REQUIREMENTS.

3.1 ITEM DEFINITION. The MRT Output Device (Printer) provides hard copy read-out capability for the serial data inputs from the MRT receiver. The printer shall receive aircraft power directly and appropriate input signals from the MRT receiver, buffer and decode those signals as necessary, and generate a high quality, high durability hard copy output using nonimpact direct imaging techniques. The printer shall use a nonmoving thermal or electrosensitive printhead.

Figure 2. Referenced specifications no. 645A094 (concluded).

be taken lightly. Not only are many of them written in precise, legally-enforceable form, but there are specialists in these fields working for the Government and for prime contractors who understand what's said in them very well.

Having made a case for taking the Applicable Documents seriously, let us now review the nature of some of them. It's particularly instructive to study the subset dealing with Reliability. Their list is repeated in Figure 3. We will now consider each of these five documents.

MIL-STD-785B	Reliablity Program for Systems Equipment Development & Production	15 Sep 1980
MIL-STD-756B	Reliability Modeling and Predictions	18 Nov 1981
Notice 1		31 Aug 1982
MIL-HDBK-217D	Reliability Prediction of Electronic Equipment	15 Jan 1982
Notice 1		13 June 1983
RADC-TR-75-22	Nonelectronic Reliability Notebook	Jan 1975
ESD-TR-83-197	Derated Application of Parts for ESD Systems Development	Sep 1983

Figure 3. Reliability references.

MIL-STD-785B, Reliability Program for Systems Equipment Development & Production, is a management document. It spells out what steps need to be taken to plan and execute an acceptable reliability program. The Table of Contents is reproduced in Figure 4. The first six pages are general in nature, including Definitions and some more Referenced Documents (see Figure 5). The meat of the documents is in the Task descriptions. Each Task is required to be executed by the contract, and many of them call out

CONTENTS

Figure 4. Table of contents, MIL-STD-785B.

APPENDIX A

APPLICATION GUIDANCE FOR IMPLEMENTATION OF
RELIABILITY PROGRAM REQUIREMENTS

Figure 4. Table of contents, MIL-STD-785B (continued).

Figure 4. Table of contents, MIL-STD-785B (continued).

TABLES

Figure 4. Table of contents, MIL-STD-785B (concluded).

MIL-STD-785B
15 September 1980

RELIABILITY PROGRAM FOR SYSTEMS AND EQUIPMENT
DEVELOPMENT AND PRODUCTION

1. SCOPE

1.1 Purpose. This standard provides general requirements and specific tasks for reliability programs during the development, production, and initial deployment of systems and equipment.

1.2 Applicability

1.2.1 Application of standard. Tasks described in this standard are to be selectively applied in DOD contract-definitized procurements, request for proposals, statements of work, and Government in-house developments requiring reliability programs for the development, production, and initial deployment of systems and equipment. The word "contractor" herein also includes Government activities developing military systems and equipment.

1.2.2 Tailoring of task descriptions. Task descriptions are intended to be tailored as required by governing regulations and as appropriate to particular systems or equipment program type, magnitude, and funding. When preparing his proposal, the contractor may include additional tasks or task modifications with supporting rationale for each addition or modification.

1.2.2.1 The "Details To Be Specified" paragraph under each task description is intended for listing the specific details, additions, modifications, deletions, or options to the requirements of the task that should be considered by the procuring activity when tailoring the task description to fit program needs. "Details" annotated by an "(R)" are essential and shall be provided the contractor for proper implementation of the task.

1.2.3 Application guidance. Application guidance and rationale for selecting tasks to fit the needs of a particular reliability program is included in appendix A; this appendix is not contractual.

1.3 Method of reference. When specifying the task descriptions of this standard as requirements, both the standard and the specific task description number(s) are to be cited. Applicable "Details To Be Specified" shall be included in the statement of work.

2. REFERENCED DOCUMENTS

2.1 Government documents. The following documents, of the issue in effect on date of invitation for bids or request for proposal, form a part of this standard to the extent specified herein:

STANDARDS

MILITARY

MIL-STD-105	Sampling Procedures and Tables for Inspection by Attributes
MIL-STD-721	Definitions of Terms For Reliability and Maintainability
MIL-STD-781	Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution
MIL-STD-965	Parts Control Program

Figure 5. Excerpt from MIL-STD-785B.

MIL-STD-785B
15 September 1980

PUBLICATIONS

MILITARY HANDBOOK

MIL-HDBK-217 Reliability Prediction of Electronic Equipment

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

3. TERMS, DEFINITIONS, AND ACRONYMS

3.1 Terms. The terms used herein are defined in MIL-STD-721.

3.2 Definitions. Definitions applicable to this standard are as follows:

a. Tailoring: The process by which the individual requirements (sections, paragraphs, or sentences) of the selected specifications and standards are evaluated to determine the extent to which each requirement is most suitable for a specific materiel acquisition and the modification of these requirements, where necessary, to assure that each tailored document invoked states only the minimum needs of the Government. Tailoring is not a license to specify a zero reliability program, and must conform to provisions of existing regulations governing reliability programs.

b. Acquisition phases:

(1) Conceptual (CONCEPT) phase: The identification and exploration of alternative solutions or solution concepts to satisfy a validated need.

(2) Demonstration and validation (VALID) phase: The period when selected candidate solutions are refined through extensive study and analyses; hardware development, if appropriate; test; and evaluations.

(3) Full-scale engineering development (FSED) phase: The period when the system and the principal items necessary for its support are designed, fabricated, tested and evaluated.

(4) Production (PROD) phase: The period from production approval until the last system is delivered and accepted.

c. Reliability accounting: That set of mathematical tasks which establish and allocate quantitative reliability requirements, and predict and measure quantitative reliablity achievements.

d. Reliability engineering: That set of design, development, and manufacturing tasks by which reliability is achieved.

e. Basic reliability: The duration or probability of failure-free performance under stated conditions. Basic reliability terms, such as Mean-Time-Between Failures (MTBF) or Mean-Cycles-Between-Failures (MCBF), shall include all item life units (not just mission time) and all failures within the items (not just mission-critical failures at the item level of assembly). Basic reliability requirements shall be capable of describing item demand for

Figure 5. Excerpt from MIL-STD-785B (continued).

maintenance manpower (e.g., Mean-Time-Between-Maintenance Actions(MTBMA)). The other system reliability parameters shall employ clearly defined subsets of all item life units and all failures.

f. Mission reliability: The ability of an item to perform its required functions for the duration of a specified mission profile.

g. Life units: A measure of use duration applicable to the item (e.g., operating hours, cycles, distance, rounds fired, attempts to operate).

h. Environmental stress screening (ESS). A series of tests conducted under environmental stresses to disclose weak parts and workmanship defects for correction.

i. Reliability development/growth test (RDGT): A series of tests conducted to disclose deficiencies and to verify that corrective actions will prevent recurrence in the operational inventory. (Also known as "TAAF" testing.)

j. Reliability qualification test (RQT): A test conducted under specified conditions, by, or on behalf of, the government, using items representative of the approved production configuration, to determine compliance with specified reliability requirements as a basis for production approval. (Also known as a "Reliablity Demonstration", or "Design Approval", test.)

k. Production reliability acceptance test (PRAT): A test conducted under specified conditions, by, or on behalf of, the government, using delivered or deliverable production items, to determine the producer's compliance with specified reliability requirements.

3.3 Acronyms. Acronyms used in this document are defined as follows:

CDR	-	Critical Design Review
CDRL	-	Contract Data Requirements List
CFE	-	Contractor Furnished Equipment
DID	-	Data Item Description(s)
ESS	-	Environmental Stess Screening
FMECA	-	Failure Modes, Effects, and Criticality Analysis(es)
FRACAS	-	Failure Reporting, Analysis(es), and Corrective Action Systems
FRB	-	Failure Review Board
FSED	-	Full Scale Engineering Development
GFE	-	Government Furnished Equipment
GIDEP	-	Government/Industry Data Exchange Program
GPR	-	Government Plant Representative(s)
LSAP	-	Logistic Support Analysis Program
LSAR	-	Logistic Support Analysis Records
MCBF	-	Mean-Cycles-Between-Failures
MCSP	-	Mission Completion Success Probability
MTBCF	-	Mission-Time-Between-Critical Failures
MTBDE	-	Mean-Time-Between-Downing Events
MTBF	-	Mean-Time-Between-Failures
MTBMA	-	Mean-Time-Between-Maintenance Actions
MTBR	-	Mean-Time-Between-Removals
PA	-	Procuring Activity (including Program/Project Offices)

Figure 5. Excerpt from MIL-STD-785B (continued).

PCB	-	Parts Control Board
PDR	-	Preliminary Design Review
PPSL	-	Program Parts Selection List
PRAT	-	Production Reliability Acceptance Test
PRST	-	Probability Ratio Sequential Test
RDGT	-	Reliability Development/Growth Test
RFP	-	Request For Proposal
RQT	-	Reliability Qualification Test
SCA	-	Sneak Circuit Analysis(es)
SOW	-	Statement Of Work
TAAF	-	Test, Analyze, and Fix

4. GENERAL REQUIREMENTS

4.1 Reliability program. The contractor shall establish and maintain an efficient reliability program to support economical achievement of overall program objectives. To be considered efficient, a reliability program shall clearly: (1) improve operational readiness and mission success of the major end-item; (2) reduce item demand for maintenance manpower and logistic support; (3) provide essential management information; and (4) hold down its own impact on overall program cost and schedule.

4.2 Program requirements. Each reliability program shall include an appropriate mix of reliability engineering and accounting tasks depending on the life cycle phase. These tasks shall be selected and tailored according to the type of item (system, subsystem or equipment) and for each applicable phase of the acquisition (CONCEPT, VALID, FSED, and PROD). They shall be planned, integrated and accomplished in conjunction with other design, development and manufacturing functions. The overall acquisition program shall include the resources, schedule, management structure, and controls necessary to ensure that specified reliability program tasks are satisfactorily accomplished.

4.2.1 Reliability engineering. Tasks shall focus on the prevention, detection, and correction of reliability design deficiencies, weak parts, and workmanship defects. Reliability engineering shall be an integral part of the item design process, including design changes. The means by which reliability engineering contributes to the design, and the level of authority and constraints on this engineering discipline, shall be identified in the reliability program plan. An efficient reliability program shall stress early investment in reliability engineering tasks to avoid subsequent costs and schedule delays.

4.2.2 Reliablity accounting. Tasks shall focus on the provision of information essential to acquisition, operation, and support management, including properly defined inputs for estimates of operational effectiveness and ownership cost. An efficient reliability program shall provide this information while ensuring that cost and schedule investment in efforts to obtain management data (such as demonstrations, qualification tests, and acceptance tests) is clearly visible and carefully controlled.

4.3 Reliability program interfaces. The contractor shall utilize reliability data and information resulting from applicable tasks in the reliability program to satisfy LSAP requirements. All reliability data and information used and provided shall be based upon, and traceable to, the outputs of the reliability program for all logistic support and engineering activities involved in all

Figure 5. Excerpt from MIL-STD-785B (continued).

phases of the system/subsystem/equipment acquisition.

4.4 Quantitative requirements. The system/subsystem/equipment reliability requirements shall be specified contractually. Quantitative reliability requirements for the system, all major subsystems, and equipments shall be included in appropriate sections of the system and end item specifications. The sub-tier values not established by the procuring activity shall be established by the system or equipment contractor at a contractually specified control point prior to detail design.

4.4.1 Categories of quantitative requirements. There are three different categories of quantitative reliability requirements: (1) operational requirements for applicable system reliability parameters; (2) basic reliability requirements for item design and quality; and (3) statistical confidence/decision risk criteria for specific reliability tests. These categories must be carefully delineated, and related to each other by clearly defined audit trails, to establish clear lines of responsibility and accountability.

4.4.2 System reliability parameters. System reliability parameters shall be defined in units of measurement directly related to operational readiness, mission success, demand for maintenance manpower, and demand for logistic support, as applicable to the type of system. Operational requirements for each of these parameters shall include the combined effects of item design, quality, operation, maintenance and repair in the operational environment. Examples of system reliability parameters include: readiness, Mean-Time-Between-Downing Events (MTBDE); mission success, Mission-Time-Between-Critical Failures (MTBCF); maintenance demand, Mean-Time-Between-Maintenance Actions (MTBMA); and logistics demand, Mean-Time-Between-Removals (MTBR).

4.4.3 Statistical criteria. Statistical criteria for reliability demonstrations, Reliability Qualification Tests (RQT), and Production Reliability Acceptance Tests (PRAT) shall be carefully tailored to avoid driving cost or schedule without improving reliability. Such criteria include specified confidence levels or decision risks, "Upper Test MTBF," "Lower Test MTBF," etc., as embodied in statistical test plans. They shall be clearly separated from specified values and minimum acceptable values to prevent test criteria from driving item design. They shall be selected and tailored according to the degree that confidence intervals are reduced by each additional increment of total test time.

4.4.3.1 Electronic equipment. For electronic equipment, the "Lower Test MTBF" shall be set equal to the minimum acceptable MTBF for the item. Conformance to the minimum acceptable MTBF requirements shall be demonstrated by tests selected from MIL-STD-781, or alternative specified by the PA.

4.4.3.2 Munitions and mechanical equipment. For munitions and mechancial equipment, a given lower confidence limit shall be set equal to the minium acceptable reliability for the item. An adequate number of samples shall be selected per MIL-STD-105, or by other valid means approved by the PA, and tested for conformance to reliability requirements as specified by the PA.

Figure 5. Excerpt from MIL-STD-785B (continued).

MIL-STD-785B
15 September 1980

5. TASK DESCRIPTIONS

5.1 The task descriptions following are divided into three general sections: Section 100, Program Surveillance and Control; Section 200, Design and Evaluation; and Section 300, Development and Production Testing.

Custodians:
Army - CR
Navy - AS
Air Force - 11

Preparing Activity:
Air Force - 11

Project RELI-0008

Review Activities:
Army - AR, AV, AT, ME, MI, SC, TE
Navy - EC, OS, SA, SH, YD, TD, MC, CG
Air Force - 10, 13, 17, 18, 19, 26, 95

Figure 5. Excerpt from MIL-STD-785B (concluded).

details to be specified by the Procuring Activity. Some of the tasks are of a management type; e.g. Task 101 requires the contractor to prepare a Reliability Program Plan. Upon approval by the Procuring Activity, executing this plan becomes a part of the contractual requirement. Tasks 102 through 105 are other Management tasks: they require the contractor to establish procedures to monitor/control subcontractors and suppliers; conduct reliability program reviews; implement and acceptable failure reporting, analysis, and corrective action system; and to establish a Failure Review Board. An example of a technical task is Task 201 Reliability Modeling. This calls upon the contractor to develop and implement a reliability model, using accepted procedures and assumptions, from which the expected reliability of the item during service (inactive and during mission execution) is calculated. The model is implemented by a top-down allocation of the failure budget according to Task 202 and a bottom up synthesis of system reliability from component data according to Task 203. Other technical tasks follow, including Task 208, identification of reliability critical items. The output of that task feeds directly into downstream quality assurance, maintenance and surveillance tasks.

Tasks 301 and following define the development and production tests that are required to validate the reliability model predictions and to control the quality of the reliability-critical items.

The extensive Appendix provides a brief, useful summary of the previously defined tasks, and how they apply to different phases of system procurement, and then proceeds into an extensive discussion of the tasks. This discussion is not a part of the legalistic definition of the tasks, but is designed to aid the engineer in interpreting the tasks. It includes the rationale for many of the requirements that have been imposed by the tasks. If one reads the task description only, some of them may appear clear but arbitrary. The Appendix serves to inform the readers of the reasoning behind them. It's important to note this distinction: the task description presents a brief recipe for what is to be done, without recourse to justification. The justification, and presumably the basis for any argument in favor of a waiver of one of these requirements, is found in the Appendix. The engineer does not have to study the Appendix; if he chooses he can simply obey the recipes and comply with the requirement. But if he wishes to dig deeper he can do so in an easily available document. If he wishes to dig even deeper he can consult the References given in the Appendix.

Overall, this document is still basically a management document. It tells what tasks are to be conducted, and what factors must be included in performing those tasks, but it does not provide specific rules or formulas for carrying out the technical efforts. Such rules are found in the next document in our sequence, MIL-STD-756B, Reliability Modeling and Prediction. The Table of Contents is reproduced in Figure 6. Again there is an introductory section, followed by more specific task descriptions. Figure 7 illustrates the level of detail in the tasks. At this point there are still no numbers, but the rules for manipulating the numbers are presented. These may seem somewhat obvious, and many of the rules are trivial to someone sophisticated in statistical analysis. But they are written down in an unambiguous way, so that compliance will not depend on the sophistication of the engineer doing the work.

The next document, MIL-HDBK-217D, Reliability Prediction of Electronic Equipment, presents numbers, thousands of them. Figure 8 illustrates just one page out of hundreds. This is an example of certified data. The Government has sifted through the data base (presumably using some contractor help) and decided that a reasonable and conservative prediction of reliability for transistors operating in a variety of Environments (GB, etc.) can be derived by multiplying together the indicated and specified factors. As long as a contractor can find the applicable number, and he is prepared to live with the conclusion, he cannot be contractually faulted. If he wishes to demonstrate that his transistor has better reliability than

MIL-STD-756B

CONTENTS

Figure 6. Table of contents, MIL-STD-756B.

CONTENTS (Continued)

Page

FIGURES

TABLES

Figure 6. Table of contents, MIL-STD-756B (continued).

TASK SECTIONS

TASKS

METHODS

APPENDIX A. APPLICATION AND TAILORING GUIDE

Figure 6. Table of contents, MIL-STD-756B (concluded).

These environmental considerations are handled as follows in Mission Reliability models.

1. For items having more than one end use, each with a different environment, the Mission Reliability model would be the same for all environments except that the failure rates for the various equipments of the item would be different for the various environments.

2. For items having several phases of operation, separate Mission Reliability models can be generated and predictions made for each phase of operation. The results can then be combined into an overall item model and item prediction.

2.3 How To Construct a Mission Reliability Model

2.3.1 Fundamental rules for probability computations. This section discusses the fundamental rules for probability computations that provide the basis for the derivation of the probability of survival (P_S) equations developed in Method 1001.

2.3.1.1 The addition rule (exclusive case). If A and B are two mutually exclusive events, i.e., occurrence of either event excludes the other, the probability of either of them happening is the sum of their respective probabilities:

$$P(A \text{ or } B) = P(A + B) = P(A) + P(B) \tag{1}$$

This rule can apply to any number of mutually exclusive events:

$$P(A + B \ldots + N) = P(A) + P(B) \ldots + P(N) \tag{2}$$

2.3.1.2 The addition rule (non-exclusive case). If A and B are two events not mutually exclusive, i.e., either or both can occur, the probability of at least one of them occurring is:

$$P(A \text{ or } B) = P(A + B) = P(A) + P(B) - P(AB) \tag{3}$$

The equation for three events becomes:

$$\begin{aligned} P(A + B + C) = {} & P(A) + P(B) + P(C) \\ & - P(AB) - P(AC) - P(BC) \\ & + P(ABC) \end{aligned} \tag{4}$$

This rule can be extended to any number of events.

Figure 7. Task description from MIL-STD-756B.

MIL-HDBK-217D
13 June 1983
DISCRETE SEMICONDUCTORS
CONVENTIONAL TRANSISTORS

5.1.3.1. Transistors, Group I

SPECIFICATION	STYLE	DESCRIPTION
MIL-S-19500		Si, NPN Si, PNP Ge, PNP Ge, NPN

Part operating failure rate model (λ_p):

$$\lambda_p = \lambda_b \, (\Pi_E \times \Pi_A \times \Pi_Q \times \Pi_R \times \Pi_{S2} \times \Pi_C) \text{ Failures}/10^6 \text{ hours}$$

where the factors are shown in Tables 5.1.3.1-1 through 10.

TABLE 5.1.3.1-1

GROUP I TRANSISTORS
ENVIRONMENTAL MODE FACTORS

ENVIRONMENT	Π_E	ENVIRONMENT	Π_E
G_B	1	A_{UC}	15
G_F	5.8	A_{UT}	25
G_M	18	A_{UB}	60
M_P	12	A_{UA}	35
N_{SB}	9.8	A_{UF}	65
N_S	9.8	S_F	0.4
N_U	21	M_{FF}	12
N_H	19	M_{FA}	17
N_{UU}	20	U_{SL}	36
A_{RW}	27	M_L	41
A_{IC}	9.5	C_L	690
A_{IT}	15		
A_{IB}	35		
A_{IA}	20		
A_{IF}	40		

TABLE 5.1.3.1-2

Π_A FOR GROUP I TRANSISTORS

APPLICATION	Π_A
Linear	1.5
Switch	0.7
Si, low noise, f.f.,<1W.	15.0

Figure 8. Example page from MIL-HDBK-271D.

deduced from these tables, he can do so, but the burden of proof is on him: he must convince the Procuring Activity that using a lower failure rate is acceptable by presenting appropriate theoretical and/or experimental evidence. Claiming that the requirement must be waived because otherwise he cannot meet his other contractual requirements on time is not an acceptable justification. If this situation occurs, he is in danger of being in default of his contract, and financial consequences should ensue. We are not so naive as to argue that this always works this way; but at least the framework is there to enable it to work. Furthermore, the Procuring Activity that lets a contractor off this hook runs the risk that it will be criticized when consequences become apparent to other parts of the DoD.

The next reference in this sequence is RADC-TR-75-22, Nonelectronic Reliability Notebook. This report presents hundreds of pages of tables of reliability values and confidence limits for nonelectronic devices frequently associated with electronic systems (e.g. accelerometers, actuators, batteries, connectors, meters, motors, relays, switches, transducers, valves). There are also sections on applicable statistical methods, reliability prediction and reliability demonstration tests. It is a complement for nonelectronic devices to MIL-HDBK-217D data for electronic devices.

The last reference in sequence is a document prepared by the Procuring Activity for this system, ESD-TR-83-197, Derated Application of Parts for ESD Systems Development. It requires each Program Office to select one of three Derating Levels, depending on the nature of the mission (e.g. Spaceborne equipments must be Level I). It then spells out the derating requirements for families of electronic devices. For example, ceramic capacitors defined by MIL-C-39014 must be derated by 50% in d.c. voltage and by 10°C in maximum temperature for Level I applications. MIL-HDBK-217D allowed them to be used up to the maximum rated voltages and temperatures, but with appropriate steep escalation of the failure rate, as illustrated in Figure 9. In this case the Procuring Activity, ESD, has chosen to impose the

Table 5.1.7.4-4

Capacitors, Fixed, Ceramic
(General Purpose) Base Failure Rates, λ_b(for T=85°C max rated)*

TEMP. (°C)	S, RATIO OF OPERATING TO RATED VOLTAGE 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0	.00067	.00083	.0013	.0022	.0036	.0058	.0088	.013	.018	.024
5	.00068	.00085	.0013	.0022	.0037	.0059	.0089	.013	.018	.025
10	.00069	.00086	.0013	.0022	.0037	.0060	.0091	.013	.019	.025
15	.00070	.00087	.0013	.0023	.0038	.0060	.0092	.013	.019	.025
20	.00071	.00088	.0014	.0023	.0038	.0061	.0093	.014	.019	.026
25	.00072	.00089	.0014	.0023	.0039	.0062	.0095	.014	.019	.026
30	.00073	.00091	.0014	.0024	.0039	.0063	.0096	.014	.020	.027
35	.00074	.00092	.0014	.0024	.0040	.0064	.0097	.014	.020	.027
40	.00075	.00093	.0014	.0024	.0040	.0065	.0099	.014	.020	.027
45	.00076	.00095	.0015	.0025	.0041	.0066	.010	.015	.020	.028
50	.00077	.00096	.0015	.0025	.0042	.0067	.010	.015	.021	.028
55	.00078	.00097	.0015	.0025	.0042	.0067	.010	.015	.021	.029
60	.00079	.00099	.0015	.0026	.0043	.0068	.010	.015	.021	.029
65	.00080	.0010	.0015	.0026	.0043	.0069	.011	.015	.022	.029
70	.00081	.0010	.0016	.0026	.0044	.0070	.011	.016	.022	.030
75	.00082	.0010	.0016	.0027	.0045	.0071	.011	.016	.022	.030
80	.00083	.0010	.0016	.0027	.0045	.0072	.011	.016	.023	.031
85	.00085	.0011	.0016	.0027	.0046	.0073	.011	.016	.023	.031

*Applicable to styles CKR 13, 48, 64, 72 of MIL-C-39014.
Applicable to "A" rated temperature of MIL-C-11015 as shown in type designation, e.g., CK61AW222M.

Figure 9. Example of derating levels (copy of page from MIL-HDBK-217D).

extra constraint not to operate the devices close to their limits, even if the overall system failure budget allowed the higher failure rate imposed by HDBK-217D.

In addition to these explicit reliability documents, reliability is affected by parameters incorporated into many individual device specifications. In the example above there was a MIL-S-39014 specification for a family of ceramic capacitors. This specification includes a number of constraints on the type of materials and construction that are acceptable in such capacitors for military use. Some of these constraints were probably incorporated because previous experience had indicated that reliability could be compromised otherwise.

2.2.2 Other Examples.

We have used Reliability Management as an example, because it is particularly appropriate for its close analogy with Hardness Management. But Reliability is not unique. Inspection of the list of Specifications incorporated into our sample contract reveals a similar set of documents for electromagnetic compatibility and interference, as summarized in Figure 10, and other environmental effects. In each case, there are documents that:

1. Specify management procedures to be implemented.

2. Provide technical rules for predicting bounds on the effects.

3. Provide government-accepted (i.e. certified) data that can be used in the predictions.

4. Impose verification tests to validate the predictions.

5. Provide standards to define acceptable procedures for carrying out the analyses and tests.

6. Incorporate environmental considerations, where needed, in the specifications for specific items.

MIL-E-6051D	Electromagnetic Compatibility Requirements System	7 Sep 1967
Amendment 1		5 Jul 1968
MIL-STD-461B	Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference	1 Apr 1980
MIL-STD-462	Electromagnetic Interference Characteristics	31 Jul 1977
Notice 4		1 Apr 1980
MIL-B-5087B	Bonding, Electrical, and Lightning Protection for Aerospace Systems	31 Aug 1970
DOD-HDBK-263	Electrostatic Discharge Control Handbook for Protection of Electrical and Electronic Parts, Assemblies and Equipment	2 May 1980
NACSIM 5100A	Compromising Emanations Laboratory Test Standard Electromagnetics (Secret)	1 Jul 1981

Figure 10. ECM and EMI references.

2.2.3 Application to Hardness Management.

Clearly the current situation in hardness management is far from the level of documentation available to Reliability Management. Returning to the Westinghouse specification, one hardness related document is referenced: AFWL-TR-76-147, Nuclear Hardness Assurance Guidelines for Systems with Moderate Requirements. This document was written and published by - Patrick and Ferry in 1976 as an initial and major step in translating nuclear effects expertise into specific recipes for systems applications. In particular, it established two classes of devices , HCI-1 and HCI-2, depending on the margin between device performance under nuclear stress and the system requirements. The intent was to identify the low-margin hardness-critical devices so that appropriate quality control, hardness maintenance and hardness surveillance actions could prevent a degradation that would impair system hardness. Specific margins were suggested for different effects. They were not derived by any formal process (e.g. statistical analysis), but represented the authors' best judgements on the compromise between covering the expected variations and imposing too severe a constraint on the designer.

In many subsequent applications, including our Westinghouse example, the HCI categorization suggested by Patrick and Ferry has been extended by adding an Uncategorized designation. In effect, if the margin is sufficiently large that no credible variations can jeopardize system hardness the part need not be included in any subsequent hardness considerations. This categorization is implemented by specifying the margins for each effect, as in Figure 11 reproduced from the Westinghouse specification. This procedure is not unique to the Westinghouse specification; similar procedures and margin values have been imposed on many other systems programs.

So what's wrong with that? Clearly, Patrick and Ferry started to do what we recommend. Their procedures were influenced strongly by analogy with reliability management and other commonly used military specifications. We understand that they did not intend for AFWL-TR-76-147 to be used as it has been, i.e. incorporated as the reference for hardness categorization and hardness assurance. They intended it as a first step pointing the way to such documents. It is regrettable that nine years later it is still the only hardness management document being referenced in most military procurements. We understand also that Ferry has prepared a draft of a follow-on report, and we look forward to the opportunity to study it.

So what is specifically wrong? A lot of specifics need improving and many more types of documents need to be prepared. Consider first the application of AFWL-TR-76-147 in the Westinghouse specification, and particularly the table reproduced in Figure 11. The following are just examples.

TABLE V HARDNESS MARGIN CLASS

ENVIRONMENT	Margin Class 1	2	3
Gamma Rate (Response Magnitude)	DM ≤ 10	10 ≤ DM ≤ 100	DM ≥ 100
Gamma Rate (Race Timing)	DM 5	5 DM 50	DM 50
Gamma Rate (Analog Time Ratio)	DM 10	10 DM 100	DM 100
Neutron Fluence	DM 10	10 DM 100	DM 100
Total Dose	DM 5	5 10	DM 10
EMP	DM < 10 dB*	10 dB ≤ DM ≤ 30 dB	DM > 30 dB

Margin calculation accuracy range from most accurate (1) to engineering judgment (3).

*voltage or current ratio

Figure 11. Hardness margin class.

1. Compare the margin break points for neutron fluence and total dose. In order to be Uncategorized (Margin class 3) the ratio between device tolerance and system specification need only be a factor of 10 for total dose, but a factor of 100 for neutron fluence. This implies that at a given level of risk variations in device response for neutron-induced displacement effects will be significantly larger than for gamma-induced long-term ionization effects. Data clearly disagree. The parameters that control neutron response (e.g. bipolar device base width, carrier injection level) are much more closely controlled in normal device manufacture than those that determine the total-dose susceptibility (e.g. quality of the oxide and the temperature history during device processing). Therefore, these margins should be different, probably by decreasing the neutron margin and increasing the total dose margin.

2. The margin break points for EMP are given in dB, which refers to EMP energy. This definition would be unambiguous if we were dealing with a linear system: 20 dB corresponds to a factor of 100 in energy and a factor of 10 in voltage or current at any point in the linear system. However, not only is most EMP response nonlinear at the affected device (i.e. the device almost always becomes nonlinear before it is damaged), but most hardened systems deliberately introduce nonlinear devices (e.g. voltage limiters) to protect the system from EMP. In this case the result is considerably different if the 20 dB margin is applied to the incident environment or to energy deposited in the affected device. Actually, either approach by itself can produce unreasonable answers. Consider the following cases:

a. A voltage limiter clamps the voltage applied to a downstream transistor to 10 V when excited by the specified EMP stress, increasing to 15 V when the incident field energy is increased by a factor of 1000. The transistor has a rated reverse junction breakdown voltage of 20 V and a dc power rating of 1 W. During the specified 1 μs EMP pulse it dissipates 0.5 W, and the pulse damage constant for the device corresponds to a 10 W, 1 μs pulse for the threshold of damage. Note now that this device operates within its dc rating envelope in both power and voltage as long as the voltage limiter does its job, even if the applied EMP field were increased by a factor of 30 dB. Common sense would say that it should be Uncategorized. However, if the margin is applied to the energy dissipated in the device, instead of the external field, it would have to be assigned to HCI-2, because the power dissipated in the device during the pulse is less than 1000 times the damage threshold for the same pulse length. If this device dissipated only 0.1 W of power in normal operation, which is certainly reasonable for a 1 W transistor, it would be categorized HCI-2 even for a zero EMP induced stress! This argument would lead us to applying the margin to the external field rather than to the energy deposited in the device.

b. Now modify the foregoing example by changing the device breakdown voltage to 9 V and making the energy delivered to the device by a 10 V pulse passed by the voltage limiter equal to 50% of the damage threshold. If the margin is applied to the external field the device is Uncategorized: the energy delivered to it is less than the expected damage threshold even when the incident field energy is increased by 30 dB. But consider what is happening to the device. It can undergo avalanche breakdown, even at the specified field without margin, and the energy delivered to it is within a factor of two of the estimated damage threshold. There exist many data to demonstrate that the damage threshold is distributed very widely: the standard deviation in a log normal fit to the distribution is usually greater than a factor of two. Thus a device that undergoes breakdown and is within a factor of two of its failure energy deserves a lot of attention, probably circuit redesign. This illustrates that there are situations in which at least part of the margin must be applied to the energy deposited in the device, especially when the device is driven into an abnormal state (e.g. breakdown).

We recently encountered exactly this situation on a subcontract to perform hardness validation analysis for individual modules of an Air Force system. Since the referenced specifications were ambiguous, as illustrated above, we offered an unambiguous definition, specifically:

1. The first 10 dB is applied to the environment. If the expected device failure level is above the specification but below the 10 dB margin it falls into category HCI-1. If, however, the device is still within its commercial or MIL-SPEC ratings with the 10 dB margin, it is Uncategorized.

2. If the device is driven into an abnormal state at the 10 dB level, the energy deposited in it during the excitation is compared to the damage threshold. If there is at least a 20 dB margin, then the device is Uncategorized. Otherwise, it is assigned to HCI-2.

This recommendation recognizes that the largest uncertainty is needed to cover the variation in damage thresholds for devices driven into breakdown. Such a margin is not needed if the device is stressed within its rated envelope, because it is designed and constructed to operated within that envelope with high confidence.

This discussion is intended to demonstrate that the first steps toward implementing our recommendations have been taken, but that the results are far from complete and the rate of progress in recent years has been far below optimal. The steps that have been taken are good analogies to Reliability and other -ilities. Acceptance from the system development community has been excellent. Consider the fact that AFWL-TR-76-147 is currently being cited in many contracts, even though it has not been through the MIL-STD review and publication process. System personnel would much rather cite a reference, especially one that has the approval of the appropriate expert community, compared to having to generate their own recipe for dealing with a problem that they don't really understand.

2.3 TYPES OF DOCUMENTS.

2.3.1 General.

At present there are three principal documents associated with Hardness Management that apply to most major system development programs:

1. DoDI 4245.4 demands that the responsible Service consider nuclear survivability requirements for each proposed new system, and that an appropriate combination of means be incorporated into the system specifications to meet those requirements. One of the means of promoting survivability is nuclear hardness; others include deception, mobility, hiding,

etc., which impose different characteristics on the system. In this report we will deal only with the hardness issues. The DoDI also defines survivability (including hardness) inputs to the various program milestones, and the incorporation of nuclear survivability inputs to the DSCARC review process.

2. Each Service has published a procedure by which the specific nuclear survivability requirements for each system, major and non-major in the DoD sense, will be established. For the Army this is published in AR-70-60, Army Nuclear Survivability. This document, as well as its Air Force and Navy counterparts, establishes a General Officer committee, the Nuclear Survivability Committee (NSC), with the authority to specify the survivability requirements. Actually, the committee meets rarely, but they motivate a secretariat, the Nuclear Survivability Committee Secretariat (NSCS) to perform the necessary studies, analyses and tradeoffs whereby a reasonable requirement is defined. The result of this process is incorporated into the systems requirements documents, usually in the form of nuclear environment specifications that the system must tolerate without unacceptable performance degradation. The exact definition of acceptable performance during nuclear exposure is usually not addressed, and becomes the subject of ongoing negotiations between the system developers and user representatives.

3. Eventually, all the requirements for the system are incorporated into specifications in the contract for system development and manufacture. Normally, the nuclear environment specifications are passed on in this contract. Sometimes, additional specific tests are required to demonstrate some measure of compliance with the environmental tolerance, although

the issue of success criterion for these tests is rarely discussed. Another usual feature is the requirement that the contractor develop, for Government approval, a plan for the hardening and hardness validation efforts. It's usually not clear what's supposed to happen if the Government doesn't approve the plan. Historical practice has been to negotiate a compromise between what nuclear effects experts believe is needed, what the contractor has proposed, and what the SPO is willing to fund.

Beyond this point there are a plethora of useful and unuseful documents that discuss nuclear effects problems and describe possible hardening techniques. The most important shortcoming to these documents is that they are not in a form useful for establishing contractual compliance; i.e., they do not establish an objective standard for success. Another major shortcoming is that many of the documents contain a finite admixture of incorrect information, which those who are not nuclear effects experts will not be able to distinguish from the important data.

We will now discuss the type of documents that need to be extended and prepared to formalize Hardness Management.

2.3.2 Hardness Management Document.

This document is addressed to managers (e.g. the Program Officer and his senior staff in the Procuring Activity; the Program Manager, Chief Engineer, Hardness Manager, etc in the development contractor). It should tell the managers what they need to know and do in order to achieve a system where hardness is validated in a cost effective and timely manner. In particular, it should include:

1. A brief qualitative summary description of the nuclear effects to be considered. This should not attempt to go beyond the minimum needed for the managers to have sufficient understanding to make intelligent judgements about programatic matters.

2. A sequence of hardness related events that need to take place for a successful program. These start with receiving the system performance and adverse environment specifications, as determined and approved by the responsible Service. They proceed with identifying the tasks needed to translate these into the form suitable for competitive procurement and contract awards, setting up the organization required to monitor compliance with the requirements, developing suitable hardness validation procedures, and meeting the various milestones for the Service SARC (e.g. ASARC) and DSARC reviews. These descriptions do not include the technical factors by which these tasks will be accomplished: that's reserved for a different document. This document is for the manager who needs to remember to have someone do the required technical tasks, and needs to review the result for meeting the programmatic requirements.

3. A list of organizations (e.g. staff functions, review groups) and responsibilities that are consistent with normal program execution, by which the hardness-related issues are best addressed.

4. Examples of procedures that have been successful, or are considered likely to be, for providing the management incentive by which cost-effective hardness is accomplished.

5. A catalog of resources (e.g. documents, agencies, facilities) that are available to support the management and technical efforts required for a successful hardening program.

One of the key parameters for this document is that it must be short. One can not expect program managers, with multi-dimensional demands on their time, to pore over a multi-hundred page document just to learn to manage hardness. Instead, a short document with a good index, and easy to comprehend recipes for doing things will be used because the manager finds that it simplifies his job. A long document that dwells on the problems instead of solving them only complicates his job. He doesn't need that.

2.3.3 Hardness Validation Methodology.

The key to any hardening program is the methodology that is used to validate that adequate hardness has been achieved. No matter how sincere the dedication and motivation of the participants in a development program are, they naturally keep in conspicuous view the means that are going to be used to grade their success. A baseline assumption, which will not be far off in practice, is that the hardening program will accomplish just enough to pass the validation requirements. Therefore, achieving adequate hardness to an operational nuclear exposure requires that the validation methodology be sufficiently congruent to operational conditions. In effect, a reasonable set of analyses and tests need to be formulated so that success (according to predefined criteria) in the validation program provides acceptable confidence of survival under operational conditions. This requirement imposes an enormous challenge to the understanding of nuclear effects. Since it's clearly impractical to reproduce all parameters of a realistic scenario, an understanding of the relevance of each parameter is needed to decide which can be compromised, which have to be compensated by an appropriate margin, and which have to be considered carefully in a validation program. Similarly, the roles of analysis and test tasks have to be integrated effectively. Analysis is always required to perform the final bridging to operational reality. Analysis can also serve to predict responses when sufficient understanding is available. Tests need to explore uncertainties that are beyond reasonable analytical capability. Unfortunately, there is a tendency to perform those tests that are easiest and least expensive; but they usually address the areas that we understand the best, i.e. those in which analysis may come closest to the answer without test data.

This discussion introduces the importance of the Validation Methodology, and indicates the intense stress its development places on our understanding of nuclear effects phenomenology. We will now indicate some of the features of a Validation Methodology document.

1. The document is introduced with a discussion of those nuclear effects to be covered and the type of systems to which it applies (i.e. the scope of the document). In the process, sufficient discussion of the technical aspects of the nuclear effects is given to provide the potential user with sufficient understanding to perform his function. In this case the user is still primarily in a management role, but is more technically oriented than the managers addressed in the previous document. Therefore, the technical discussion, while it should still be brief, goes into more technical depth than in the Management document.

2. The document considers each of the relevant nuclear effects, and integrates them into a combined validation methodology in which stresses are combined in the most effective manner. For example, displacement effects from neutrons and long-term ionization effects from gammas both produce cumulative degradation in the important properties of semiconductor devices.

The validation program should consider each at the device level, but combine their effects into a single device degradation factor before incorporating the result into the circuit functional analysis. Similarly, some nonnuclear environments produce stresses similar to some nuclear stresses (e.g. lightning and HEMP). The analysis and test program should consider these specifications together, even if the dominant frequencies of the excitations are different, because the techniques used to perform the calculations, to apply test stresses, and to diagnose equipment response are similar.

3. The document does not present only a single approved validation methodology, but defines the rules for constructing any of a number of approved methodologies out of building blocks: individual analysis and test tasks. All of the blocks are identified, together with references to Standards documents that define adequacy criteria for their application, and the means whereby a satisfactory Methodology can be constructed are spelled out, but each development organization is allowed to choose among these options.

4. The methods (building blocks for the Methodology) include a hierarchy of sophistication, cost and accuracy. Each method is accompanied by a margin that must be validated when using that method. The margin is defined by the Government to be sufficient to overcome all know uncertainties in applying the method. Presumably, the least costly methods will also have the larger margins imposed on them. This places the developing organization in the position of properly conducting the tradeoff between margin (which may be costly in hardware) and validation methods (which become more costly as the available margin becomes smaller).

5. Examples of Validation Methodologies should be given to illustrate how to develop one from the information given in the document.

The principles to which we adhere in this approach are:

1. The development organization should be provided as much tradeoff room as possible to achieve an optimum development program, in which hardening is one, but only one, vital dimension.

2. The tradeoffs should be performed subject to constraints on sufficiency defined by the Methodology document.

3. Systems development organization will be motivated to incorporate design margins when that results in a savings in validation costs.

2.3.4 Specification Formats.

We have already referred to the environmental specifications that are currently written into many hardware contracts. Through experience and review these are now presented in reasonably complete and standard forms, and are mostly adequate. However, this specification is only a small part of the total. Specifications need to be incorporated into the entire contract tree extending from the prime item to the individual piece part provided by a vendor to a subcontractor.

To some degree many of these contract interfaces will affect the nuclear hardness of the system. It's impractical to educate all the specification writers in this chain to be nuclear effects experts. Therefore, it's important to provide guidance on how to write specifications that include nuclear effects in such a manner as to be effective and appropriate to the item being purchased. The need for this is clear. For example, we recently performed an HEMP hardness validation analysis for an Army equipment, for which the electrical stress was specified by a voltage/current and pulse length, but no rise time. Since parasitic coupling (e.g. buried circuit excitation) is strongly dependent on the high frequency content of the electrical stress, this specification was clearly insufficient. We suggested a reasonable rise time, which was accepted by our customer, and proceeded with the analysis. However, this was clearly an unsatisfactory situation for a mature discipline. There should exist suitable formats into which the specific equipment numbers can be inserted, but which ensure that all of the relevant numbers are included.

In some cases the nuclear effects community should go beyond that point and provide a complete specification. The case of HEMP is an example: the fact that the appropriate HEMP environment specification is almost independent of the target system or battlefield scenario implies that a single integrated HEMP specification applying to a large range of target equipments is appropriate. This recognition led DNA to play the major role in the development of DoD-STD-2169, which presents such a specification. The more common case, however, is where the individual values of the stresses vary greatly between applications. For example, a single specification for HEMP stresses to electronics boxes would not be useful; the actual voltages/currents on the wires and the skin currents on the boxes are a strong function of the external wiring geometry and enclosure shielding as well as the single HEMP field environment. In this case, the appropriate document is a specification filled in with TBD to indicate the numbers that must be inserted for each application.

2.3.5 Standards.

We define a Standard as a prescription for an item, process, or procedure. Some standards define an item; e.g. MIL-C-39014 described the minimum acceptable characteristics of a ceramic capacitor. Standards also may define a process; some features of a device may be determined by defining the process used to make it. Standards also define procedures, ranging from management procedures (e.g. the reliability management standard discussed above) to analysis and test procedures (e.g. a standard for measurement of neutron fluence and spectrum). In effect a Standard controls the quality of something; those parameters that need to be bounded to achieve the desired result must be addressed by the Standard. The Standard is written in recipe form. It may have some introductory tutorial information, and perhaps an explanatory Appendix that describes the rationale for the recipe but basically the recipe is the key operative content. As such the Standard should have the force of a legal document: a nontechnical lawyer should be able to determine whether it has been complied with.

2.3.6 Certified Data.

There is no formal requirement for the Government to supply certified data for the Hardness Validation process. Given a complete set of Standards by which acceptable data can be generated, the validator has at his disposal all the means necessary to accomplish the process. However, it is inefficient for many organizations to duplicate efforts (e.g. test the same devices). It is even more inefficient for validation efforts to address issues that could not possibly jeopardize the hardness of a system just because there appears to be a formal requirement to do so. For example, we have recently performed a number of neutron fluence analyses for systems in which the threat fluence was well below 10^{11} n/cm^2 (1 MeV equiv). There are very few semiconductor devices in which any significant effects occur at these low fluences. A quick evaluation whether such sensitive devices are present should serve to complete the validation. Nevertheless, the whole procedure implied by AFWL-TR-76-147 was required with a foregone conclusion: there were no hardness critical items because of neutrons. This same conclusion could have been derived at much less cost if the Government had certified a simple worst-case formula for neutron damage, and reasonable implications of using worst-case results (e.g. do not apply additional margins if the result is already truly worst case). Many other examples can be found. The reason for supplying such data is strictly economic: the taxpayers money can be diverted to addressing more significant issues by providing some information as given and acceptable to the Government.

There must be some caution in the definition of certified data. Not all Government provided data is certified. For example, in the area of neutron effects some worst case formulas based on the physics of devices and studies of data banks would be reasonable candidates for certified data. The actual data in the DASIAC data bank should be provided as useful information, but would not be certified. The user would have to apply the rules contained in Standards to those data to determine which are appropriate for incorporation into his validation tasks.

2.3.7 Guideline Documents.

Guideline documents serve to provide useful information for the managers and engineers conducting a nuclear hardening program. They are designed to be informative and useful, but do are not mandatory in the contractual sense. There is no requirement to follow the guideline recommended practices. Their only persuasion is the quality and usefulness of the material contained. Among other subjects, guidelines could address recommended hardening techniques, specific instrumentation practices for tests, and the means whereby the numbers could be derived to fill in the specification formats.

It is sometimes tempting to include nonmandatory guideline information in the more formal contractually-required documents, e.g. Standards, Specification Formats, and Methodologies. We recommend against doing so in the main body of the document, because it might lead to misinterpretation between mandatory and advisory material. It is suitable to include the guideline material in an Appendix, where it's readily available and the difference status is apparent.

2.3.8 Tutorial Documents.

Tutorial documents, e.g. textbooks, are needed to train personnel in all phases of nuclear hardening and testing, ranging from test technicians to nuclear effects experts. These also are not formally imposed on system development, but are made available to those who wish to receive the education. It's particularly important for there to be a range of textbooks; i.e. different ones for training experts who intend to advance the state of nuclear effects knowledge than those intended to train engineers for whom nuclear effects is only one of many subjects competing for their attention.

2.3.9 Technical Support Documents.

We have emphasized the formal nature of the Standards, Methodologies and Specification Formats, indicating that they should present an easily followed, unambiguous recipe to which a lawyer could judge compliance. This does not leave much room for explanatory material or for technical justification of the rules. It's nevertheless important for the technical basis for each rule to be clearly established in a form subject to ongoing review. That's the purpose of Technical Support Documents. These present a technical audit trail on which each rule is based, including the supporting data and analyses. These documents form the basis for future improvements to the rules, identify the areas in which research is needed to refine or support rules, and can be the starting point for a review of a waiver request from one of the rules. While these documents do not present any information with which the development organization is required to comply contractually, we believe it is essential for these documents to be prepared. Otherwise, the basis for the rules would soon become unclear, and future generations of technologists and engineers would waste a lot of time arguing about their adequacy.

2.4 UNCERTAINTIES, STATISTICS, AND MARGINS.

2.4.1 Introduction.

The process of nuclear hardness assessment or validation is beset with many uncertainties. Since the possibility or adequacy of a particular nuclear hardness validation process is frequently questioned on the grounds of uncertainty, we will address this subject explicitly. In order to provide additional insight into the problem we will define three classes of uncertainties: parameter variations, modeling uncertainties, and evaluation approximations. It is apparent to all workers in the field, and especially to critics of hardness validation methodologies, that there are many uncertainties and some of them cover a wide range of values. It is not difficult to construct a hardness validation approach whose application can be reduced to the ridiculous if one tries to incorporate all of these uncertainties.

The process of hardness validation is frequently confused with hardness assessment. We will offer distinct definitions of these two terms. We will define hardness assessment as a process by which investigators generate the best estimate of the hardness level of a systems hardness level (stress level at which it reaches its threshold of failure), together with estimates of the distributions of the hardness levels and the uncertainties in making the estimate. Hardness validation, on the other hand, is the process by which investigations establish that the system meets its hardness requirement. Hardness validation is not concerned with an accurate estimate of the threshold for system failure; it is directed at establishing at a reasonably high level of confidence, that the system will not fail at and below a given level of environmental stress.

These two processes are frequently intermixed because the methods that are used to achieve a hardness validation or similar to those used for hardness assessment. It is also true that an accurate hardness assessment, which incorporates all variables and uncertainties in a high-confidence determination of the probability of system failure as a function of environmental stress, would immediately generate the hardness validation. One simply has to evaluate the probability of failure at the particular value of environmental stress corresponding to the system specification to determine whether the hardness had been adequately validated. Unfortunately, it turns out that an accurate determination of the probability of failure versus environmental stress is an extremely difficult task, which is beset with all the uncertainties and variations that we will discuss below. Therefore, it is not surprising that hardness validation based upon applying hardness-assessment methods does not lead to a high confidence conclusion.

<u>For this reason we offer the suggestion that hardness validation be approached from a significantly different point of view than hardness assessment</u>. Hardness assessment is concerned with generating the maximum likelihood estimates of the probability of system failure as a function of environmental stress. The uncertainties in these estimates can go both ways. There are factors that might make the system harder than this estimate, other factors make it softer. <u>Hardness validation is concerned only with a one-sided answer: that the hardness is at least as great as the specified level. For this reason, it is appropriate to incorporate into hard</u>ness validation one-sided estimates, such as worst-case values of parameters and expected responses. This process would not be valid for an unbiased hardness assessment, but it is applicable to a legalistic hardness validation.

Once one accepts the idea of using bounds as a way of overcoming uncertainties, it also leads naturally to a choice of methods by which the bounds are derived. Usually one can establish bounds to various phenomena, including nuclear effects, using very simple principles, although such bounds may be far from the maximum likelihood expected response. For example, in EMP problems it is always possible to bound the amount of available energy by using the Poynting vector and the effective target cross section of the system. The target cross section has a maximum value dependent upon its physical size and the wavelength of the electromagnetic radiation interacting with it. Clearly, it doesn't require much effort to calculate this bound on the available EMP energy. Unfortunately, this answer is almost always useless, because this bound on the available energy is much greater than the amount of energy needed to produce significant damage in individual electronic devices. Therefore, it is necessary to work harder, e.g., to evaluate bounds on the attenuation factors that are interposed between the external energy fluence and the potentially effected electronic devices before one can generate an inequality on which hardness validation can be based. These calculations can also progress at the various levels of detail, each with a corresponding degree of conservatism. For example, simple inspection of a metallic enclosure can assure that the electromagnetic energy flux inside the enclosure will be attenuated by a factor of 40 dB compared to the external flux. It takes an easily noticeable penetration for the magnetic field inside a metallic exposure to be greater than 1% of the incident field. On the other hand if a 40 dB worst case attenuation factor does not produce a useful hardness validation answer, it may be necessary to perform electromagnetic attenuation measurements over the range of EMP frequencies. For example, it's probably necessary to perform ongoing hardness maintenance and surveillance activities to demonstrate that the actual shielding factor is maintained at a level of 80 dB or greater. The moral of this example is that when we are fortunate to have a significant margin available, relatively simple analyses can serve to establish with high confidence that the hardness is validated. When we are not so fortunate, more elaborate processes are needed to bring the bounds closer to the expected values. The key issue in hardness management is to identify the candidate methods for placing useful bounds on nuclear effects. The methods can consist of using the maximum likely estimate as in a hardness assessment and adding an additional safety factor to the answer to create a reasonable bound. In other cases, the methods can be fundamentally different when one is seeking a bound rather than a maximum likely estimate.

2.4.2 Uncertainties.

We will discuss three classes of uncertainties that effect hardness assessment and that have to be compensated by margins and bounds in hardness validation: parameter variations, modeling uncertainties, and evaluation approximations.

2.4.2.1 Parameter Variations.

It is well recognized that some parameters that describe the nuclear response of a system have large variations. In the case of transient radiation effects in electronics (TREE) these variables include the variation response of the individual units for a particular device type. The EMP variations will include not only the variation in susceptibilty threshold of the electronics devices, but also variations in the geometry that determine the coupling of electromagnetic energy from the incident EMP to the electronic devices. Some of these parameters can vary widely, because they may be not closely linked to the parameters that control the ordinary functional response of the device or enclosure. For example, enough is understood about the long-term effect of ionizing radiation on semiconductor devices to realize that the effect can vary by more than an order of magnitude depending upon the purity of the oxide grown on the semiconductor device and of the temperature history through which the device must go subsequent to oxide formation. Parameters that determine the radiation response of the oxide are only weakly linked to those that determine the normal electrical function and reliability of the device. For example, both radiation and reliability are degraded by having a sodium ion contamination in the oxide, but the normal function of the device appears to be aided by hydrogen atoms, whereas the radiation susceptibility is significantly degraded by their presence. One approach to nuclear hardening is thus to insist that all possible relevant parameters of electronic devices and assembly are controlled so as to preclude significant variations in nuclear response. This approach, we believe, is impractical. It devotes a lot of resources to controlling parameters most of which will turn out not to effect the hardness of the system.

Among relevant parameters there are three kinds of factors that promote variations: *initial, temporal, and scenarios.*

The initial variations of parameters are those which exist at the time that the system is manufactured. Where needed, these variations are reduced by quality control. In order to achieve cost-effective hardening, it is important to minimize the number of parameters that must receive extraordinary quality control.

Temporal variations are those that occur with time during normal system storage, deployment and operation. For example, the normal air environment, especially those near the ocean, can degrade the contact between metal surfaces by forming oxides and other non-conducting films on metals. To some extent the performance margin that may exist in a semiconductor device between its requirements and its initial characteristics may be eroded with time as a result of slow diffusion of species or action of the ambient environment on surfaces. Other temporal changes occur as a result of specific steps taken during the normal life cycle of a system. For example, routine maintenance actions may require that hatches or inspection parts be removed and replaced. In this process it is possible that electrical gaskets are damaged, or even left out by the maintenance personnel, when the system is reassembled.

There are major variables in the scenarios as well. While a specification is usually intended to be a single or small set of worst-case threats to the system, the actual operational environment will have a large range of variables in it. These include variables to describe the stresses imposed on the system (e.g., spectrum, range and incidence angle). Other environmental variables may be relevant to the system response (e.g., atmospheric pressure) and a large number of variables describe the configuration in which the system finds itself at the instant of exposure (e.g., the specific state of the electronics, as well as features of the mechanical configuration).

2.4.2.2 Modeling Uncertainties.

The expected response of a system to a given nuclear-induced stress is usually synthesized by combining data on the response of part or all of the system under somewhat different stresses into a model that predicts the operationally significant response. If accurate reproductions of the operational conditions were available and reasonable to use for test programs, this model would reduce to the simplistic one which says that the operational response will be identical to the test response. In all nuclear effects cases, there is a wide chasm between reasonably available data and operational situations. This chasm must be bridged by some type of modeling effort, which incorporates the available data and our understanding of the relationship between response and conditions into a prediction of the operational response. Such a model can be as simple as a few words that indicate the underlying assumptions and establish a relationship between test stress and operational stress. Or it could be as complicated as a large scale computer code. In either case there are significant uncertainties of three types: simplifications, perception errors, and missing phenomena.

Simplifications are those steps taken in the modeling process, whereby complicating features of the system or its interaction are deliberately left out because, in the judgement of the modeler, they do not significantly alter the conclusion of the modeling effort.

Perception errors are somewhat more insidious. These represent differences between the modeler's perception of the system/exposure and reality. Presumably, the modeler included all of the parameters that he recognized as being important. There are numerous examples of nuclear effects analysis (especially in EMP) in which test results revealed a parameter (e.g., a coupling path) that the modeler was not even aware of at the time he did his predictions.

The third area is potentially the most disquieting, but in practice is the least often encountered: missing phenomena. Clearly, if the model did not include a process that isn't even understood to be relevant, the prediction can be far off. This uncertainty has some of the same character as the perception error. In both cases it is the result of something being overlooked in the modeling process. However, the perception error can always be detected by performing suitable investigations on the hardware. The missing phenomenon is more difficult to expose, because without a knowledge of the phenomenon a judgement cannot be made on the appropriate means of exposing the unknown phenomenon. Clearly, as experience is gained in a field and more test results under different conditions are accumulated, the chances of there being an undetected phenomenon decreases, while it is never possible to prove the absence of the unknown unknown (unk. unk.), it is not the subject of overriding concern at this time.

2.4.2.3 Evaluation Approximations.

The third class of uncertainties involves the procedure by which numerical evaluations are made, either analytically or experimentally. For example, computer programs performing complex calculations are limited in their accuracy, even when the computer appears to be performing the calculations to many significant features. There are many ways in which codes can generate inaccurate answers because somewhere in the computation small differences of very larger numbers are calculated. It requires a great deal of critical evaluation of results generated over long periods of time in the use of any computer code before confidence in its accuracy is achieved. Experiments are also subject to uncertainties. There are the obvious inaccuracies in the measuring equipment and there are the less obvious errors introduced by electrical noise, sensor interference, and just plain human error.

2.4.3 Statistics.

Statistical methods can be powerful aids in dealing with some of the uncertainties discussed above. They are particularly useful in describing the variations in device parameters, and in synthesizing system response variation from such data. They are not applicable to perception errors or to the estimation of the risk of missing phenomena. Any estimate of the risk of making such errors must be subjective, and is not amenable to objective statistical treatment.

Statistical methods are generally of two types: parametric and nonparametric. Parametric methods are based on an assumed distribution of the variables . The conclusions are dependent on the validity of that assumption, although with sufficient data the consistency of the assumed distribution can be checked. Non-parametric statistics methods make no such assumption, and the conclusions are valid for any underlying parameter distribution from which the data could have reasonably been derived.

Clearly, from a standpoint of rigor, non-parametric statistics are preferred. Unfortunately, in most nuclear-effects applications, applying non-parametric statistics to data that can be acquired with reasonable resources results in conclusions that are so weak as to be uninteresting. For example, consider performing a particular test on a number of units of a military system to draw a conclusion about nuclear hardness, observing on each test whether the item's response during and after the test is acceptable (i.e., setting aside the qualitative issue of the interpretation of the test results in terms of operational stresses). A reasonable goal of such a test is to establish with 80% Confidence that 90% of the units would survive such a stress. Such a conclusion could be drawn if 15 units were tested without a failure, or 30 units with only one failure. Considering the difficulty and expense of nuclear effects tests, and the good chance that apparent failures occur during major test programs that probably have nothing to do with the nuclear stresses, imposing such a requirement can be very costly. When this is compounded with questions, such as the effect of life-cycle operation and maintenance on the system (i.e. do they have to be repeated periodically?), the non-parametric approach appears to be of limited use.

The parametric approach assumes that some parameter of interest (e.g. the stress level at the threshold of failure) is distributed according to some formula, and that tests are used to measure the parameters of that distribution. Commonly used distributions include Normal, Lognormal, and Weibull. For parameters that are inherently positive (e.g. the failure stress), we prefer the Lognormal over the Normal. When the standard deviation (i.e. second moment or variance) is small compared to the mean (i.e. first moment), these two distributions become the same. When the standard deviation is not small compared to the mean, the Normal distribution is not meaningful for an inherently positive quantity, because it has a significant value for zero and negative arguments. The Lognormal distribution, instead, is not meaningful for negative arguments.

The consistency of an assumed distribution with the data can be checked by well-established numerical tests. Given an assortment of N data, not only can we calculate the attributes of an assumed distribution (e.g. the mean and standard deviation of a Lognormal distribution), but also evaluate the likelihood that the N data came from a Lognormal distribution. Unfortunately, this evaluation is likely to detect significant deviations only if they occur at the 1/N level in the probability distribution. For example, a tail in the underlying probability distribution that occurs at the 10^{-3} level is unlikely to appear if the sample size is only 100. Therefore, such tests are useful in establishing the consistency of the data with an assumed distribution, but they can never prove that the distribution is correct at probability levels beyond those at which data exist. Unfortunately, the need for parametric methods is precisely in these limits: to extrapolate limited statistical data to useful probability levels at which we cannot afford to treat data nonparametrically.

Therefore, there is a valid criticism that the validity of parametric statistics can not be proven out to the probability levels that need to be used for practical conclusions. This criticism is answered in two ways:

1. Since applying nonparametric statistics with reasonable investments in testing does not produce useful answers, taking the risk of assuming a parameter distribution to generate useful answers seems to be the lesser of the risks.

2. Since there is some risk involved, it is important for the government to control that risk by specifying the acceptable assumptions, as it has traditionally done in Reliability, and thereby controlling the methods to be applied by individual systems programs.

3. The methods to test the validity of the statistical assumptions should be applied to the broadest data base possible, in order to perform such tests to as low a stress-probability level as possible. For example, if the form of a distribution is assumed for a class of electronics parts responses, and the assumption is made that different members of the class (e.g. different part types) differ only in the distribution parameters (e.g. mean and standard deviation), then the consistency of the distribution assumption (e.g., Lognormal) can be checked by renormalizing all data for all members of the class by the distribution parameters evaluated for the individual members of the class. In other words, the data can be replotted on a single distribution by dividing each datum by the mean for its type, and raising the result to a power which is the reciprocal of the standard deviation for the type; i.e.

$$S^* = (S/S_m)^{1/\sigma}$$

Where S^* is the normalized value of S, whose mean is S_m and standard deviation σ. The lognormal distribution, S^*, has a mean of unity (log = 0) and a standard deviation of e ($\ell n = \pm 1$).

4. Since there remains some risk that an undetected tail on a failure distribution causes operational problems, there remains a continuing need to perform some "realistic" integral tests on operational-type equipments. Since there are a lot of additional hidden variables in testing complicated equipments, these cannot serve as a basis for statistical evaluations. Instead, they are another means of minimizing the risks incurred in the statistical approach, which

relies on simpler tests to generate the data. In our approach, there is some question as to whether the government or the development organization should accept the risk of failure in such an integral test, but there is no question that the developer must demonstrate compliance with the parametric statistical methods, as defined by government provided standards.

2.4.4 Margins.

Margins play a key role in engineering design to meet adverse environmental influences, including nuclear effects. As suggested before, it's not reasonable to base the design and validation on an accurate representation of the system's response to an adverse stress; the cost of generating and applying the data can far exceed the benefit to be derived. Instead, the cost-effective approach is to use worst case limits to establish that the system will respond within acceptable performance envelopes to the entire range of adverse stresses. Design margins are frequently used to establish this result. For example, if it can be established that the margin between the worst case initial gain of a transistor and the minimum value required to perform a circuit function is greater than the worst case degradation caused by the specified neutron and gamma exposure, together with a suitable allocation for in-service degradation, then it is established that the transistor is not critical to the required hardness of the system. Similar inequalities can be applied to other hardness related features, such as the quality of the electrical shielding.

The foregoing discussion illustrates how a margin can be used to compensate for the variables in nuclear-induced degradation of electronic parts or assemblies. A margin can also be used to compensate for approximations made in the hardness validation process. For example, consider the case in which the transistor gain margin is not sufficient to compensate for the worst possible degradation. Then test data may be required to establish the adequacy of the design. The tests can be performed on a range of sample sizes, the larger the size the more accurate the statistical conclusions but the more expensive the test. There exist standard statistical procedures by which margins are applied to small-sample data to compensate for the smallness of the sample (e.g. K_{tl} tables for samples from normal distributions). If there is sufficient design margin to accomodate a larger K_{tl} factor, a smaller sample size is satisfactory. If not, a larger sample size is required.

This same concept of applying margins to simplify validation methods extends to analytic methods. An EMP coupling calculation can be performed at many degrees of sophistication, ranging from simple hand calculations to three-dimensional computer modeling. The hand calculation is satisfactory if a margin applied to the result to account for its approximations can be tolerated by the system design; otherwise, a more accurate, and presumably more costly method, is required. If too many structural details become involved in the assessment, it's probably necessary to perform a test to validate the hardness. In this case, we are faced not only with the cost of a realistic test, but also the prospect of having to repeat it occasionally as part of a hardness surveillance program. Clearly, a margin incorporated into the design can save a lot of money downstream during hardness validation, hardness assurance, hardness maintenance and hardness surveillance.

2.5 ANALYSIS/TEST HIERARCHIES.

The discussion in the previous section on Margins, and especially some the examples, leads directly to a hierarchical approach to analyses and tests. <u>Our recommendations follow the tradeoff philosophy established earlier: margins can be traded off against complexity in validation methods.</u>

In the past, where required analyses and tests were specified in the contractual documents at all, the analysis/test requirements were specific, or at least were intended to be. As discussed previously in Section 2.2, there were ambiguities in the interpretation of the results, particularly in the success criteria. However, the developer has not usually been offered any options: each defined analysis and test task was to be performed, and its performance was independent of the design (hopefully, the result depended on the design). In some cases, there have been debates within government circles, aided and abetted by industrial experts, on whether some tasks were required or not. Usually, the final word on these arguments has been fiscal: things do not get done if no one supplies the money to do them. Other arguments are based on test quality (e.g. the debate over whether B-1 should be exposed to TRESTLE), and on the possibility of misinterpreting the result if it's influenced by the lack of realistic simulation fidelity.

Our recommendations offer a distinct variation to this theme. The contracts should not specify all of the specific tests and analyses to be performed, but specify the rules whereby a specific set of tests and analyses can be selected by the developing organizations. In general, these rules are such as to motivate the designers to incorporate margins in their designs. These margins do not allow a hardness issue to be ignored, but they enable simpler methods (which require larger margins to be justified) to demonstrate that hardness has been achieved.

Consider the example of the SGEMP hardness of a spacecraft. A favored approach to hardening a spacecraft with respect to a variety of electromagnetic stresses is to enclose the electronics and cabling in electrical shielding compartments (so-called Faraday cages), and to control the signals that must pass into and out of those compartments. It was argued by some satellite designers that, since their satellite used this approach, the issue of SGEMP generated external to the cable shields was irrelevant, and no analysis or testing would be required. It was argued by some nuclear-effects experts that the quality of the shielding needed to be verified, and that a realistic stress test was required whether the electrical shielding were incorporated into the design or not. Our approach to this conflict is this: if the electrical shielding is more than adequate to provide protection from external and cavity SGEMP excitation, this can be demonstrated to anyone's satisfaction with a modest electrical test program: injecting electrical currents into the spacecraft structure and cable shielding and verifying that the signals coupled into critical circuits are well below the threshold for functional disturbance. This injection test, since it involves relatively efficient conversion of electrical energy in the simulator (or stimulator), can easily be performed at a level far enough above the expected threat level to compensate for uncertainties in reproducing realistic current distributions and waveforms. This approach provides the basis for an intelligent tradeoff: if the margin is sufficient and the developer has confidence in it, a simple test serves to demonstrate that the margin exists. If the margin is not sufficient to utilize the simple test, a more complex validation method is required, with the attendant extra costs and risks.

Incorporating this approach into the legalistic form of contractual specifications requires that the government define all of the validation method options and the margins that must be applied for each method and the Standards that control the application of each method. Once this is provided, a legally enforceable framework exists within which the developer can choose the approach that minimizes costs and risks to himself while being assured that the government must accept the results if they are satisfactory according to the pre-defined rules.

2.6 ZONE CONCEPT.

The zone concept is another means by which the developer can trade off complexity for accuracy in the nuclear effects validation tasks. Under a particular realistic nuclear stimulation (radiation or electrical) each portion of an electronic system is exposed to a particular level of excitation. It is very costly to determine the excitation at each of many locations for each of many exposure conditions, and then to evaluate the electronics response to each of the exposures in terms of the different excitations of different parts. Consider the specific case of X-ray exposure. A detailed modeling of an electronic system in sufficient detail to calculate the particular dose deposited in each electronic device, and to repeat that calculation of each possible exposure orientation and spectrum, would be an expensive proposition. Instead, it is customary to use worst case values (e.g. the dose at devices located at the surface of the electronics assembly) to establish satisfactory operation. In effect, this approach neglects the shielding that is provided by other electronic devices, at least for some exposure orientations, but includes the shielding provided by the enclosure and deliberate overall shields. The problem of calculating the dose as a function of spectrum, or at least the worst case dose (usually associated with the hottest spectrum) is considerably simplified by using this single worst case dose. However, there is a penalty to this approach: the electronics must be sufficiently tolerant of the exposure that any device could perform its function in spite of this dose, even those that are fortunate enough to be located inside the electronics assembly where they receive additional shielding from other devices. This approach could lead to unnecessary hardening. In that case, it would be better to consider those devices that are located more deeply in the electronics assembly separate from the ones near to a surface, and perform two calculations of worst-case dose: one that applies to the set of devices near the surface and another for the more heavily shielded devices. It might even be prudent to incorporate a deliberate extra shield for some particularly sensitive devices, and a special calculation applies to them. In this case, the electronics has been partitioned into three zones for purpose of X-ray dose calculations. Each device is assigned to one of these zones, and its response is evaluated with respect to the worst- case dose in that zone. The developer has the option of defining as few or as many zones as he chooses: the more zones provides the ability to have less margin between device tolerance and actual exposure at the expense of additional calculations. Fewer zones decrease the validation cost, but at the expense of additional dose tolerance margins for those devices that are more heavily shielded than the worst-case members of their zone.

The same approach applies to other excitations. It is usually trivial for gammas and neutrons, because the shielding provided by typical electronics for these high-energy particles is little enough that it rarely justifies using more than one zone. It is particularly important for EMP excitations, because there the zones are determined by a combination of radiation shielding (for IEMP type excitations) and electrical shielding. There are some natural barriers between zones, which contribute greatly to EMP protection at relatively little cost. Those barriers almost certainly need to divide different zones. Consider a typical electronics system consisting of a number of chassis located inside a room with cabling extending between chassis and to the outside world. The room itself provides some protection from the externally imposed EMP field, and the excitation of the conductors external to the building is much greater than any internal excitation. Therefore, separating the external cable excitation from the internal cable excitation is fruitful. If, in addition, some interface protection is applied where the conductors penetrate the building wall, a considerable reduction can be achieved. The same argument applies at the electronics enclosures, which are usually metal boxes with a considerable electrical shielding effectiveness. Not only are the fields inside the boxes much less than outside, the length of wiring with which the fields can interact inside the boxes is also much less than the inter-box wiring. Furthermore, if some of the cabling happens to be shielded, it's prudent to define an excitation zone inside the shield separate from the outside. This example illustrates the motivation for adding zones: additional zones are worthwhile when the barrier between them contributes a significant reduction in stress. On the other hand, it's possible that the electronics has been designed with enough margin that the extra barriers are not needed for EMP protection. In that case, the extra zones are not needed in the validation.

Thus we again see that having relatively few zones is desirable for simplicity, but where additional zones contribute significantly to achieving hardness at less cost they are justified. Again there is an easy way to incorporate this approach into the legalistic contractual procedures: the developer has the option to define as few or as many zones as he wishes as long as within each zone the excitation at any point is assumed to be as much as the worst-case excitation within that zone for the worst-case exposure condition.

The zonal method also merges well with the Hierarchical approach. In practice, the developer would start performing the validation tasks assuming relatively few zones for each type of excitation. Where the margins permit him to derive a satisfactory conclusion, no further work is required. Where the conclusion is unacceptable, additional zones can be defined as well as additional refinements in the validation analysis or test method. Presumably, this process will lead to an acceptable conclusion; if not, redesign is required. It is the responsibility of the developer to have created a design for which this process converges. There is no escape, such as stopping short of an acceptable answer when money or time run out.

2.7 EFFECT OF MARGINS ON HARDNESS ASSURANCE/MAINTENANCE/SURVEILLANCE.

The previous subsections have illustrated a recommended relationship between design margins and the complexity of hardness validation methods (e.g., analysis/test, number of zones). There is also an effect on steps in hardness management beyond hardness validation: hardness assurance, maintenance and surveillance (HAMS). This relationship was proposed in the pioneering work of Patrick and Ferry, AFWL-TR-76-147, and has been applied to a number of subsequent electronic systems developments. In effect, the philosophy is that larger margins allow less concern about HAMS.

Design Margins when applied to electronic components result in their allocation to various Hardness Critical Categories (HCC), each of which carries with it testing requirements of varying degrees of complexity and cost. The definition of design margins, as applied in the categorization process has, therefore, a major impact upon costs during design, production and maintenance.

Two different part categorization methods have come into use: the Design Margin Break Point (DMBP) method, and what we will call the Part Failure Budget Method (PFB) method.

The first of these is applicable to systems with moderate requirements and involves the application of a discrete set of categorization criterion to all parts of the system. The basic assumption involved is that even under worst-case conditions, the moderate system requirements can be easily met. The DMBP method is intended to greatly simplify Hardness Assurance Design Documentation (HADD) by the application of a single simple rule to all parts of the system. It has the disadvantage of leading to overdesign in some cases with a large number of parts being assigned to the more critical part categories and therefore requiring expensive test procedures. This method has been used by both the Air Force and the Army.

The Part Categorization Criteria method is designed for application to systems with higher level requirements. In this case separate categorization criteria are applied to each part type. The PCC approach can lead to substantially fewer parts being assigned to the most critical category with a consequent reduction in testing requirements and reduced costs over the life cycle of the system. The disadvantage is complication of the HADD because each part could have a different categorization.

2.7.1 Design Margin Break Point Method.

In my DMBP method a single set of design margins is defined for a given effect and a large family of part types. The margins must be large enough to compensate for the worst variations that could be encountered in the family.

The design margin is defined in terms of mean values at the radiation specification level for the system and at the failure level of the part type. For example, it is common practice to define the design margin in terms of failure fluence or dose versus specification level e.g.,

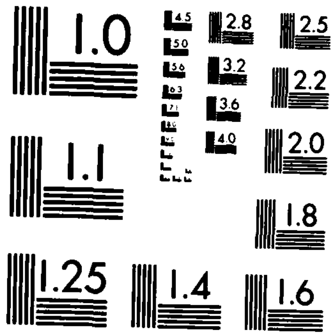
$$D.M. = \Phi_{FAIL} / \Phi_{SPEC} \text{ or } Dose_{FAIL} / Dose_{SPEC}$$

The results obtained are then compared to preassigned values used to categorize the parts e.g., those shown in Table 1.

Table 1. Example of parts categories.

Design Margin	Category	Action
$D.M. < 2.0$	Unacceptable	Redesign
$2.0 < D.M. < 10$	HCC I	Lot Test[illegible]
$10 < D.M. < 100$	HCC II	[illegible]
$100 < D.M. < 1000$	Non Critica[illegible]	[illegible]

AD-A188 193 NUCLEAR HARDNESS MANAGEMENT(U) MISSION RESEARCH CORP 2/2
SAN DIEGO CA V A VAN LINT ET AL. 28 FEB 86
MRC/SD-R-174 DNA-TR-87-54 DNA001-83-C-0115
UNCLASSIFIED F/G 19/11 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Unfortunately a variety of design margin definitions have appeared in the literature. The definitions are not consistent and recent official documentation (e.g., MIL-HDBK-279) has not adequately distinguished between the different definitions. Costly errors and misunderstandings can result as pointed out in Appendix A.

An alternative to defining design margins in terms of environmental levels is to use device parameter values

$$D.M. = PAR_{FAIL}/PAR_{SPEC}$$

where PAR_{FAIL} is assigned on the basis of a worst case-circuit analysis and PAR_{SPEC} is determined experimentally by exposing a sample of parts to the specified radiation limit. In the past, it has not been stressed sufficiently that the approach using device parameter values will only yield results that are consistent with the environmental definition when the device response is strictly proportional to environmental exposure. Unfortunately, cases where this condition is violated are more frequent than those where it applies, especially in complex microcircuits. The result can lead to considerable confusion.

Another problem in applying this method in the past is that assignment of values to the design margin break points were influenced more by the effect on design (i.e., how much margin could be tolerated without significant effect on equipment design) than by the underlying variations in part response that the margins is to compensate for. For example, a smaller margin is sometimes assigned to total dose levels than to neutron fluences, even though the variations in semiconductor device response is usually larger for the long-term ionization effect.

2.7.2 Part Failure Budget Method.

In the PFB method the failure budget for the system for each effect is distributed among all the parts in a manner such as to minimize the overall hardening and HAMS cost. For each part type the validation and HAMS activities are then chosen to control the part contribution to overall system failure to be within its budget. Since the individual part contributions to a realistic system failure budget must be very small, a form for the underlying statistical distribution must be assumed to yield useful results at reasonable costs (i.e., we must use parameteric statistics).

As applied, the statistical approach assumes that the radiation results on components can be satisfactorily described by a lognormal distribution (see Appendix B). In this statistical treatment the old definition of design margin is retained. However, the part categorization assigned is made contingent upon the degree of variability for the part type and its consistency with the failure budged assigned to the part. The problem of nonlinearity in device response still leads to discrepancies when categorization is based upon parameter ratios rather than the ratio between environmental failure and specification levels.

SECTION 3
METHODOLOGY EXAMPLES

3.1 INTRODUCTION.

In this Section we will attempt to demonstrate the practicality of the recommended approach by outlining two sample methodologies: EMP Hardness Validation and TREE Hardness Validation, both for typical tactical Army applications.

3.2 EMP HARDNESS VALIDATION.

The inputs for EMP hardness validation of an electronics system are:

1. One or more specified EMP environments, generally in the form of a waveform or frequency spectrum for a TEM free-field radiation incident on the system.

2. A definition of what constitutes acceptable operation by the electronics system.

3. A description of the system, and possibly one or more systems or subsystems for inspection and/or testing.

The outputs of the validation task are:

1. A conclusion, if warranted, that the system, as designed and constructed, will perform as required in spite of single or specified multiple exposures to the EMP environments.

2. Identification of those elements of the design whose margins are insufficient to assure continued hardness during serial production or routine operation and maintenance.

As stated, the outputs do not require a fragility curve: i.e. the relation between probability of malfunction and the level of EMP environment. This would be a different requirement, which requires different methods to satisfy, than strictly hardness validation. It's to be emphasized that hardness validation, as defined, is an asymmetrical objective: it's only required that the system perform satisfactorily at a given stress level. It's not necessary to determine the level at which it will fail. Uncertainties in the analysis can be resolved by a conservative approach (i.e. worst casing). This cannot be done if a fragility curve is required. It demands a symmetrical approach, with uncertainty bands superimposed. For this reason, deriving a fragility curve can be a much more difficult and expensive undertaking than hardness validation.

This approach also has its counterparts in other disciplines. Systems do not usually require a fragility curve with respect to shock and vibration, only a validation at specified excitation levels.

The validation process may include analyses and tests. The analyses and tests may be simple or complex. The goal is to achieve the required outputs at the minimum expenditure of resources. The asymmetric approach promotes this: the methods are applied in a step-wise manner. If a simple method produces the required result, no further effort is required. This will occur particularly when the design incorporates a significant margin between the nominal capability and the requirements.

3.2.1 Analysis Methods.

The first step in hardness validation analysis is partitioning: the interactions leading from the incident EMP environment to the electronics response are partitioned for individual attention. This is done best by zoning: defining spatial regions within each of which there is a single worst-case definition of the EMP stress levels. All of the equipment must be contained within one or another zone. There is no other formal constraint on the zoning. For convenience, the zone boundaries usually follow physical barriers (e.g. conducting surfaces) across which electrical transmission is naturally inhibited.

The second step is establishing worst-case excitation levels for each zone. This must take into account the excitation levels in adjacent zones and worst-case leakage through the zone boundaries.

The third step is to bound the effects of the worst-case electrical excitations on the electronic devices and circuits located within each zone.

Hardness validation testing can be conducted at any level of excitation and assembly corresponding to this view, depending on the nature of the uncertainties that must be addressed by testing. Uncertainties in coupling between one zone and another (e.g. between the externally incident field and internal wire currents) can be addressed by one type of testing. Uncertainties in circuit response to a given worst-case current/voltage transient on the interconnecting wiring requires a different test. Performing a check on the analysis by exposing a realistic system to a threat-level simulator is another type. <u>The rule should be that the uncertainties to be addressed be defined, and that the test be the simplest one that will resolve those uncertainties</u>.

In the following subsections we will illustrate the hierarchy of methods available to perform each of these types of tasks.

3.2.1.1 Zoning.

Formally, the methodology requires that the entire physical space occupied by the system be divided into clearly defined zones: there must be no ambiguity as to which zone any portion of the equipment occupies. There is no a priori specification on the number of zones: the validator can choose as few or as many as he wishes to achieve the objective. The trade-off is produced by the fundamental requirement that for each zone there is a single worst-case set of electrical stresses: all equipment within that zone must tolerate those stresses. If only a few zones are defined this may force some equipments to tolerate much larger levels than actually required. If too many zones are defined the complexity of the analysis increases. In principle, this definition even allows wire-by-wire circuit-by-circuit analysis: each wire and circuit are a separate zone. In practice this approach is costly, inefficient and unnecessary.

Each zone requires a clear definition of its boundary, which also defines what zones are adjacent to it. If two zones are defined so that there is an electrically transparent boundary between them, the worst case excitation levels can not be much different in the two zones, and not much is gained by defining separate zones rather than combining them into one. This argues for defining the zone boundary at naturally occurring electrically attenuating surfaces (e.g. conducting layers).

In systems subjected to the external EMP radiation, one of the zones should always consist of the exterior of the system: i.e. the region in which the incident field is specified and interacts with the exterior enclosure, and earth if appropriate. As a minimum, normally a minimum of two other zones would be defined: one for the interior of the overall enclosure (e.g. building or missile skin) and one for the interior of electronics boxes. Additional zones would be defined as needed, e.g. to distinguish between spatial regions in which the electrical excitation is significantly different (such as ones near or far from dominant penetrations), or to distinguish between different levels of electrical protection.

The topology of the zones can be complex if necessary. For example, if a particular physical region contains both unshielded and shielded cables, it may be prudent to define a separate zone for the interiors of the cable shields. This allows the currents and voltages on the inner conductors of the shielded cables to be smaller than the excitations of the unshielded conductors or the shields on the shielded cables. In some cases, the zone inside the cable shields may be an extension of the zone inside electronics boxes connected to the cables.

Across each boundary between zones, all means by which electrical energy can penetrate must be identified. Normally, this includes the natural attenuation of the layer (as a function of frequency, of course) as well as the transmission characteristics of imperfections in the layer (e.g. apertures, seams, insulated conductors).

Conventional EMP hardness analysis follows this approach, more or less. What needs to be added is a degree of formality: specific definition of the zones, the equipments within each, and the penetrations between them.

3.2.1.2 Zone Stresses.

The next step in the analysis is to establish appropriate worst-case electrical stresses for each zone. These stresses include electric and magnetic fields, which may couple to conductors and excite barriers to adjacent zones, as well as currents/voltages on conductors. In both cases the frequency spectrum of the excitations are important, or at least some characterization of excitations within ranges of frequencies. The controlling requirement is that the derived stress levels represent the worst cases to be encountered within the entire zone. If it's necessary to make an exception of a subset of the space or of some conductors in the zone, these become part of a separate zone.

The methods by which these stresses are derived range from simple estimates to complex computer calculations, each with a corresponding margin applied to compensate for uncertainties. The excitations for each zone consist of :

1. The currents and charges (i.e. magnetic and electric fields) on the outside of the boundary surfaces between the zone and adjacent zones.

2. The magnetic and electric fields in apertures through the boundary surface.

3. The currents and voltages on conductors that penetrate through the boundary surface.

Usually, the only excitations that need to be addressed are those applied to the zone by zones in which the stress levels are larger than the selected zone stress levels.

Translating the adjacent-zone excitations into the selected zone excitations requires consideration of intervening protective layers or devices. The detail to which those layers/devices need to be modeled depends on the degree of protection required. For example, a conducting box can assure at least 40 dB of magnetic shielding near 10 MHz, even if it's not provided with special gasketing and it includes small apertures. If much larger shielding effectiveness is required, the details of the apertures and seams may have to be considered to draw a valid conclusion.

Conductors that penetrate from one zone to another are a particularly important source of excitation: both by conducting electrical signals to electronic devices and by generating magnetic (mostly) and electric fields inside the inner zone. If conductors penetrate directly from one zone to another, without encountering a protective device (e.g. limiter, filter), the worst-case conductor excitation must be the same for both zones. It's also likely that the electric and magnetic field excitation of the inner zone are determined by the penetrating conductors. For many applications, the excitations levels for the two zones would become the same, and there is no advantage to separating them by an ineffective barrier: i.e. the two zones could more easily be treated as one.

If there are protective devices on the conductors at the interface between zones, the characteristics of the devices and their installation determine their worst-case transfer function. Again, if high levels of isolation are required, small details of their construction and installation may be important (e.g. the length of the wires on a voltage limiter determine the inductance in series with the limiter and may degrade the high-frequency (i.e. fast-rise) response. Again, the sophistication of the modeling and analysis method is determined by the degree of isolation required.

3.2.1.3 Equipment Response.

The zone stresses established above include bounds for all the relevant stresses within a particular zone, i.e. including voltages and currents (as a function of frequency or time) on all the conductors leading to electronic devices. The next step is to determine whether these stresses can be tolerated by the devices and circuits, i.e. whether the equipment will continue to perform its required function in spite of exposure to the stresses. This analysis is best separated into two parts: damage and upset. The damage analysis addresses the possibility that individual electronic devices may suffer permanent degradation in performance characteristics as a result of the stresses. The upset analysis addresses the possibility that the electronics function can be disturbed without permanently damaging any device.

a. Damage Analysis.

The specifications for each electronic device include the range of electrical parameters (e.g. voltage and current) over which the device is designed to function. For example, transistor specifications include BV_{ceo} and BV_{beo}, the minimum values of the collector-emitter and collector-base voltages, respectively, at which breakdown could occur. These values do not imply that breakdown will occur at these voltages, only that they won't occur at lesser voltages. Similarly, there are usually specifications on maximum steady-state power dissipation or maximum emitter current. For complex microcircuits the maximum values are usually simpler: maximum values of the power supply voltage and the requirement that all terminal voltages remain between the most positive and most negative power supply voltages. <u>The key point of these specifications is that they are not subject to the type of statistical variations experienced in testing semiconductor devices</u> for electrical damage threshold. These limits are maintained by normal process control, and can be used with confidence for the entire population of devices. Prudent design cautions engineers to maintain some margin in actual applications to allow for other variables, e.g. temperature, ageing, power fluctuations. However, it's reasonably safe to assume that EMP induced transients that, combined with normal operating voltages, do not exceed these specifications will not damage the devices. This is the first level of analysis: determine whether the upper-bound transients in a zone are within the rated maximum stresses for the devices.

The next level in the analysis hierarchy assumes that transients that exceed the normal ratings for long-term stresses can be tolerated to some degree under short-term excitation. In other words, semiconductor junctions can be driven into Zener or avalanche breakdown without permanent damage, as long as the duration of the excitation is short enough. This is the subject addressed by most research on EMP effects on electronic devices. It is within this realm of excitation that wide statistical variations have been reported. The difficulty has been attributed to the creation of narrow current filaments within a device by instability mechanisms. It is reasonable to assume that damage to an electronic device will only be produced if the temperature in some part of that device exceeds a threshold value. If a large volume is heated simultaneously by the excitation the energy required is large; if only a small filament is heated, failure can be produced by much less energy. For longer pulses there is an inherent limit to the heated volume: the dimensions are at least as large as the thermal diffusion length. This line of thought was developed into a prediction method for a lower limit on the damage threshold of semiconductor junctions (Ref. 1).

Other methods of establishing analytical bounds on the tolerance of electronic devices to electrical overstress have used experimental data, adding margins for statistical variations, and have used device specification sheet data, also with margins to compensate for additional uncertainties. Unfortunately, most of these efforts have attempted to describe the actual failure levels, rather than concentrating on safe operating limits. We believe that a careful review of all these sources of information will reveal that:

1. There are useful lower bounds on the electrical overstress energy below which damage is not observed.

2. The voltages at which these bounds are encountered are not very much larger (i.e. not by more than a factor of 2) than the rated maximum operating voltages in complex microcircuits.

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1. van Lint, V.A.J. and R.E. Leadon," Hardness Assurance Implications of Variations in Junction Burnout", Vol. NS-24, No. 6, 2084 (1977).

3. Considering the wide spread of experimental data on electrical overstress failure energies, it would be imprudent to assume satisfactory operation at any larger stresses than the conservative bounds.

The implication of these statements is that the safest approach is to limit the stresses to the electrical specifications. The next safest approach is to use a conservative analytical bound on the allowable overstress energy. Beyond this point, the only reasonable recourse is an ongoing program of device sample testing, with all the accompanying implications of hardness assurance, maintenance and surveillance. Clearly such cases should be limited to special needs.

Another implication of this approach is that the insertion of voltage limiters at the interfaces between the internal and external wiring is a particularly powerful hardening method. These devices can clamp the transients at levels intermediate between normal signal voltages and the breakdown ratings of the devices inside the electronics box.

b. Upset.

Upset is more difficult to deal with in general, because the stresses that can produce functional upset are within the range of normal operating parameters. For example, a digital logic circuit that changes state when the input voltage changes from 0 to 5 V will do so whether the change is produced by an upstream circuit or by an EMP-induced transient.

Therefore, the hierarchy for upset analysis follows a different route than damage analysis. The first step is the same: determine whether the upper-bound transients are large enough to cause any recognizable disturbance. Instead of comparing the transients with breakdown voltages, they are now compared with noise margins (e.g. typically 1 V for TTL circuits).

Unless the external protection has been very thorough, the result will be that such disturbances are possible, not only in circuits connected to wiring leading out of the electronics boxes, but also induced inductively into wiring inside the electronics box.

The most powerful analysis technique for eliminating upset modes is functional analysis of the electronics. The nature of the electronics function and how it accomplishes it frequently eliminates most upset concerns. The following examples illustrate this point.

Most electronic subsystems are designed to perform a function that is inherently slow on an EMP time scale: e.g. missile steering, voice communication, navigation. The output circuits that actually command the function are usually slow: a short lived transient is hardly noticeable. However, the determination of the function is sometimes performed by faster circuits (e.g. a digital computer). Even then, the input data used by the computer may also be relatively slow (e.g. accelerometer inputs). Moreover, a major portion of the electronics is the power supply, in which large capacitors are used to stabilize the output. A priori, this description leads naturally to the principal suspect for upset: the digital computer, or, more generally, digital circuits.

Even digital circuits don't necessarily imply upset susceptibility. Consider a digital gate network, in which the output at any instant is determined by the state of all the inputs. If the inputs are controlled by slow actions, and the output only affects slow circuits, the transient disturbance will go unnoticed. On the other hand, if the network includes latching devices (e.g. flip-flops or memory cells), the state in which the circuits are left after the transient may be different than the state in which it started, and malfunction is possible.

Sometimes, even in memory circuits, upset is not produced by transients. For example, a common practice in issuing discrete commands is for a circuit to perform a given operation a number of times (e.g. 3) before the result is accepted and acted on. The likelihood of three EMP exposures producing the same affect at the required time intervals is negligible. Therefore, the more likely failure is that the EMP disturbed the issuance of the discrete if it occurred during the correct small time window. This illustrates an important aspect of upset: many electronic subsystems have small windows in which they may be particularly susceptible to upset. The system specifications must address the tolerance level for such windows.

Finally, there is the digital processor. It's clear that a general purpose digital processor is likely to be disturbed unacceptably if logic level signals (>1 V) with durations comparable to clock pulses (generally fractions of a microsecond in high speed computers, slower in some special purpose machines) are inserted into their internal wiring. Specific hardening is still possible (e.g. by active circumvention), but is not likely to be found in Army tactical equipments. Clearly, the first line of defense in this case is to suppress the transients below the noise margin of the circuits. This clearly cannot be done with voltage-limiting devices at the interfaces: normal operating signals will exceed the noise margins. It can be done with filters, if the frequency spectrum of normal operating signals is much different (higher, as in radios, or lower, as in power and slow signals) than the EMP-induced transients.

This discussion is not to imply that upset analysis is easy; it is not, and there are an enormous number of special cases. The discussion is intended to imply that such analysis, intelligently approached, is practical. It also illustrates that the approach is different than damage analysis: it takes an electronics functional point of view rather than a device point of view.

3.2.2 Testing.

EMP hardness validation testing has more options than analysis. It can cover either the same partitioned subjects discussed above, or it can combine a number of them. There are two fundamental choices in a test: the excitation and the diagnostics. Overlaying this choice is the matter of excitation level: for linear interactions the excitation can be any level that provides adequate signal compared to noise in the diagnostics. For nonlinear problems, the excitation must be related to the realistic stresses.

A prudent means of test planning is to decide first the nature of the uncertainties to be resolved by the test. This is best done within the context of the analysis. Examples are:

1. There is insufficient margin available to use a simple coupling bound. Therefore, an accurate measure of the coupling across one or more zone boundaries is required.

2. There is insufficient margin available to use generic device susceptibility thresholds. Therefore, statistically valid data on particular devices is required.

3. Additional confidence in the upset analysis is required, because there are so many possible upset modes.

4. High confidence in the hardness of a few critical equipments is required. An integrated test would provide confidence that the analysis has not overlooked a critical issue.

Each of these uncertainties leads to a different type of test, e.g.:

1. A low-level coupling test, perhaps swept CW, to measure the frequency characteristics of the dominant coupling mechanisms.

2. A step-stress-to-damage test on a large lot of each device type.

3. An electrical injection test on the electronics box with realistic waveforms, probably with breakout boxes at the cable connectors.

4. A realistic free-field EMP illumination of the electronics and associated structure, combining both electronics functional diagnostics and selected internal excitation measurements.

It's apparent from the foregoing example, that there is a tradeoff between analysis and tests, and between test complexity, cost and realism. As before in the case of analysis, the existence of margins in the design will allow simpler test to suffice.

3.2.2.1 Excitations.

The choice of test excitations requires first the determination of excitation level requirements. If the assumption of linear response is acceptable, more options are available. If this assumption is not acceptable, the excitations are limited to those that are sufficiently realistic in both amplitude and waveform. "Sufficiently realistic" means that the test margin is large enough to compensate for the degree of unrealism.

a. Threat-Like Excitations.

The simplest threat-like excitation is the free field EMP waveform, which is usually contractually specified. Actually, since it's costly to reproduce, there are usually some compromises (e.g. notches in the frequency spectrum). The seriousness of those compromises must be judged by referring to the analysis, and should be compensated by margins. This waveform is applicable only to the outermost portions of the structure containing the electronics.

The next step in threat-like excitations is reproducing the currents and electric fields on the outermost conducting boundary of the structure: e.g. the skin of an airplane. At this point the waveform is markedly different from the incident field, since the structure has superimposed its own frequency response on the frequency content in the incident field. The advantage to moving to this level of assembly is that it's much less costly *in energy and technology to reproduce the surface conditions on a finite* object than to produce the threat fields in a large volume of space. It requires an adequate knowledge of the frequency dependent transform from free field to surface fields, but these can be derived from a combination of analysis and low-level coupling measurements.

The next step in excitation involves driving realistic currents and voltages (e.g. Thevenin-equivalent sources) on the cables in the structure. Since at this point the waveforms are distorted even more by the frequency response of the complex structure and cabling topology, the demands on analysis and/or low-level coupling experiments are more severe. However, the requirements on the test facilities become much less, because relatively little energy is required to produce realistic cable excitations.

Following the excitation chain inwards, we come to the wires and pins entering electronics boxes. Again, more information is needed about coupling to define an adequate test, but it's easier to perform the test at threat levels.

Finally, there's the excitation at the individual electronic devices. In this case it's possible to generate reasonable statistical data, and to use semi-empirical scaling relations to convert data for different pulse waveforms.

b. Excitations for Linear Problems.

Once linearity can be assumed the range of possible excitations expands, as does the generalizability of the test results. This gain is the result of the superposition theorem for linear problems: not only can we scale the results in amplitude by simple multiplication, we can add the results of different excitations algebraically. This theorem is particularly valuable with respect to waveforms. The result of a given excitation can be analyzed into its frequency components (e.g. by Fourier analysis), and the results of different excitations can be synthesized from those components (e.g. by Fourier synthesis).

In the linear regime, there are two types of excitation choices: excitation waveform and excitation level. Both of these are determined by the same important criterion: signal compared to noise. High signal/noise ratios are required if detailed Fourier analysis and synthesis are to be performed. Therefore, the excitation must be high enough, and the diagnostic instrumentation clean enough, to provide the needed signal/noise ratio.

Three types of excitation waveforms are frequently used:

1. Continuous wave at various discrete frequency (e.g. swept CW).

2. Step function pulse, single or repetitive.

3. Damped sine wave pulse at various center frequencies.

The first technique enables measurements to be made with high signal/noise ratio using lock-in type detector systems. It is time consuming, since the frequency intervals between measurements should be small enough to avoid overlooking any important coupling resonances.

The step-function pulse method has the advantage that it contains a wide spectrum of frequencies, and allows the system to reveal its own resonances. In the single-shot mode it requires more excitation to achieve a given signal/noise ratio. In the repetitive pulse mode the signal/noise can be enhanced by digital signal averaging. It requires Fourier analysis of the input and output signals.

The damped-sine method is frequently used to drive electronics boxes, albeit at threat-like levels. It falls intermediately between the other two methods, because a number of frequencies are required to cover the possible resonances, but each excitation has a broader frequency spectrum than the CW method. In principle, the center frequencies should be close enough to cover all intermediate frequencies.

3.2.2.2 Diagnostics.

The second part of any test is the diagnostics: the measurements that are made to determine the response of the test object. Again these are strongly determined by the object of the test: i.e. the uncertainty it's intended to resolve. Generally, the diagnostics falls into three categories: excitation and response measurements and functional diagnostics.

We define excitation measurements as those that measure the character of the transients induced into the system, excluding the response of the electronic devices. Response measurements determine the specific reactions of the electronic devices to the electrical excitations. We define functional diagnostics as those response measurements that are directly related to the function of the electronic subsystem.

For example, consider a radio receiver under test by direct electrical injection on its cabling. Excitation diagnostics would include measurements on the pin currents/voltages. Response diagnostics would include measurements of the signals appearing within the amplifier chain. Functional diagnostics would look at the character of the information out of the radio to determine whether it was within acceptable ranges (e.g. duration of disturbance, signal/noise ratio after exposure).

The objectives of the test will strongly influence the tradeoffs that must be made in the diagnostics. Excitation and response measurements provide the best information for comparison with analysis, but introduce the risk of disturbing the test item's response. Functional diagnostics is most closely related to the system's application, and usually is easily made in a non- disturbing fashion, but provides little in the way of interpretable evidence if a surprise is found. Nor does it provide information on incipient failures, i.e. malfunctions that may occur at very slightly higher excitation levels.

3.2.3 Tradeoffs.

The foregoing outline of analysis and test methods suggests the tradeoffs for planning an EMP hardness validation methodology. Usually, the simpler analyses are less costly than tests; the simpler tests are less costly than the more realistic tests. Design margins can be used to drive the validation methodology toward the less costly options. The exact choice of methods can be tailored to the specific application. What is needed is a clear definition of how to carry out each of these methods (e.g. a Standard), accompanied by a rule to derive the margin that must be incorporated into each method's application to compensate for its uncertainties (including unrealism).

3.2.4 Application.

The foregoing subsections have outlined the methods that can be used to validate the EMP hardness of a specific electronic system. The control over these methods has to be incorporated in formal documents, including specification formats, standards, and certified data. Table 2 presents a partial catalog of documents needed to support this methodology. Clearly, even for this limited objective, there are many documents, each of which has to be prepared with care. The catalog also makes clear that the individual documents are sufficiently limited in scope to be both practical and useful. Of course, they may be bound together as a combined document, but each method should be self-sufficient.

3.3 TREE HARDNESS VALIDATION.

The inputs to a TREE hardness validation of an electronics system are:

1. One or more specified radiation environments incident on the system, including gammas, X-rays and neutrons, together with some measure of their spectra and delivery times.

2. A definition of what constitutes acceptable operation by the electronics system.

3. A description of the system, and possibly one or more subsystems for inspection and/or testing.

The outputs of the validation task are:

1. A conclusion, if justified, that the system, as designed and constructed, will perform as required in spite of exposure to one or more specified nuclear environments.

Table 2. Partial catalog of standards, specification formats and certified data EMP validation.

TITLE	PURPOSE OR CONTENTS
EMP waveform specification	Waveform specification format and actual specified EMP waveform.
Standard method for calculation of coupling to antenna	Method of calculating coupling to small antenna on the system and coupling to the system itself.
Thevenin source for long penetrating wires	Given the EMP waveform this standard calculates the Thevenin source for long wires attached to the system. Provisions for different ground conductivities are included in the calculation.
Standard method for calculation of diffusion and leakage through an enclosure	Methods of calculating diffusion and leakage through all possible points of entry.
Standard method for calculating shield currents	Methods which determine currents of induced on cables due to fields internal to the box.
Certified data of cable transfer impedances	Induces data on various types of conductors and connectors over frequency ranges of interest to EMP.
Standard method of measuring cable transfer impedance	Supplies methods to determine cable transfer impedance when it is not available in the previous document.
Standard method for calculation of Thevenin equivalent source	Provides method to calculate Thevenin equivalent source on wires from shield currents, cable transfer impedance, and source impedance.
EMP pin specification format	Specifies format of threat pulse that appears on pins.
Standard practices in EMP circuit analysis	Includes standard circuit analysis methods.

Table 2. Partial catalog of standards, specification formats and certified data EMP validation (concluded).

TITLE	PURPOSE OR CONTENTS
Device electrical response criteria	Existing document which includes methods to determine safe operating threshold regime for a device from stated specifications.
Hardness critical Categorization	Explains H.C.C. and the concept of design margins. Also included are recipes to categorize devices.

2. Identification of those elements of the design whose margins are insufficient to assure continued hardness during serial production or routine operation and maintenance.

These inputs and requirements are similar to those discussed in Section 3.2 on EMP hardness validation; only the interactions and the relevant parameters are different. As in that case, the objective is different from establishing a fragility curve. The requirement is inherently unsymmetrical: to establish that the system is tolerant to a given environment, not to establish the environment at which it will malfunction. There are other analogies, as well in the partitioning of the problem, but the relative emphasis on various means of protection is very different. Where shielding and interface limiting play a major role in EMP protection, shielding is only effective against X- rays , and protection has to be provided at the device/circuit level for the effects of TREE.

3.3.1 Analysis Methods.

As in the case of EMP the analysis divides naturally into a coupling portion - i.e. the transport of the radiation from the incident environment to the affected device - and a response portion - the response of the device to the radiation at its location. In contrast to EMP, the transport part is usually trivial for the gamma and neutron components of the radiation, and is only slightly more complex for the X-ray component. To a reasonable approximation, the transport is dependent primarily on the amount and atomic number of the intervening material, and relatively independent of other details of the geometry.

The device response is more complex, and is subject to statistical variations which are only slightly less in magnitude than for electrical excitation. In the case of radiation excitation there are not even defined safe operating levels to which electrical excitation can be reduced with confidence.

3.3.1.1 Zoning.

Since the absorption length for gamma rays and neutrons is generally long compared to the amount of intervening material for most electronic systems, it's usually adequate to define the gamma and neutron intensities at the affected devices to be equivalent to the incident intensities. For this purpose only one stress zone is required.

X-rays are a different story. For them the amount of intervening material, and especially the atomic number of the material, determines the stresses placed at the devices. Therefore, a zoning scheme similar to that used for EMP is appropriate. Again there is a tradeoff between increasing the number of zones, with the worst case environment in each zone tailored to its shielding, or decreasing the zone count with more margin required for some devices, but with considerable saving in analysis complexity.

3.3.1.2 Zone Stresses.

The zone stresses for gamma rays and neutrons are usually the same as in the incident environment. For X-rays, calculations of the shielding effectiveness are required. These calculations must take into account the Z dependence of the material absorption properties, a variety of potential directions from which the incident radiation may expose the system, and the variation of the photon spectrum as it passes through the absorbing material. There are a hierarchy of methods for calculating X-ray transport.

The simplest method divides the incident fluence into a convenient number of energy groups, and transports each group with an exponential attenuation factor determined by the effective energy absorption cross section. This calculation can be performed by hand, or , more conveniently, by a standard spread-sheet program on a personal computer. It is reasonably accurate for modest shielding factors - i.e. attenuations not much greater than a factor of 100. At the deeper locations it tends to over-estimate the stress, which is consistent with a conservative approach.

More complex calculations depend on better description of the absorbing geometry, and more detailed tracking of photon energies as they are decreased by Compton scattering. Usually, these calculations are performed on a main-frame computer (e.g. VAX ,CYBER, CRAY) using Monte Carlo programs. These programs must follow many interaction histories to generate sufficient statistics. They can be performed in 1, 2 or 3 dimensions, depending on the accuracy required and the computer budget. They can generate more accurate answers for complex geometries. One must remember, however, that if the difference between the accurate answer and an approximate one is significant, the control of the variables entered into the more complex calculation (e.g. the geometrical description of the system) is also critical. All too often much effort is expended on an accurate radiation transport calculation for an ill-defined or ill-controlled geometry, or when the statistics of device response far outweighs the uncertainty in radiation exposure.

3.3.1.3 Equipment Response.

As in the case of EMP, electronic equipment responses to radiation can be categorized as damage and upset, depending on whether there is a relatively permanent degradation of device characteristics. There are some additional complexities associated with short-term annealing (especially in time scales of less than 1 sec) of the damage.

a. Damage Analysis.

Damage analysis involves two parts: establishing the device parameter bounds for acceptable circuit function, and establishing the device response to the given radiation stress. At one time establishing acceptable device parameter bounds involved much complicated circuit analysis, because the individual circuits were custom designed from discrete components. In many modern electronics most of the functions are performed by microcircuits, which have certain inherent performance requirements. More or less a microcircuit function defines acceptable performance, as distinct from a transistor, whose satisfactory performance depends on the specific circuit in which it's incorporated. There are some variables in microcircuit performance. The range of power supply voltages over which it will perform acceptably is one. Another, for high speed circuits, is the maximum clock frequency at which it will perform satisfactorily. For analog circuits there is also the gain-bandwidth product, and sometimes input offsets. In digital circuits there is also fanout, which determines the maximum number of inputs driven by an output. Nevertheless, these requirements can usually be determined much more easily than the analysis of a typical discrete-part circuit.

Both ionizing radiation (gammas and X-rays) and displacing radiation (e.g. neutrons) can produce permanent damage in electronic devices, especially semiconductor devices. As distinct from EMP, in which the damage tends to be catastrophic, TREE manifestations are mostly in the form of gradually increasing degradation as the exposure increases. The variations in response of supposedly identical devices is a serious problem, because the variables that determine the radiation response, especially to ionizing radiation, are not tightly controlled by the manufacturing process.

Nevertheless, there are some simple techniques available to the analyst if the margin is sufficient. For example, in both bipolar and FET devices it's possible to establish an upper limit on the rate at which displacing radiation (e.g. neutrons) can produce damage. This upper limit can be determined from device characteristics reported in their specification sheets (e.g. breakdown voltages and frequency-band width product). If this worst case response is acceptable, no further analysis or testing is required.

Similar upper limits can be established for long-term ionization effects in semiconductor devices, but they are not as useful, particularly in MOSFET and high performance OpAmp applications.

The next level of analysis uses device test data for similar generic devices. There are large variations in test results for each type of device, and between manufacturers, and between lots for a given manufacturer. However, if the margin is sufficient to encompass these variations, a safe conclusion is justified.

Finally, one may have to resort to testing to generate acceptable response data. Unfortunately, this almost always means that the margin is insufficient to avoid ongoing testing to meet hardness assurance, hardness maintenance and hardness surveillance requirements.

b. Upset Analysis.

Upset analysis for TREE excitations is similar to the EMP problem discussed in Section 3.2.1.3. Again a functional analysis, the same functional analysis required for EMP, is the best screen to eliminate most potential problem spots.

Generic upset thresholds of microcircuits can be used with considerable confidence. In general, the variation of upset threshold is not nearly as large for a given device type as the variation in long-term ionization damage.

3.3.2 Testing.

The foregoing discussion of EMP testing has a direct analog in TREE applications. The purpose of the test - i.e., the uncertainty it is to resolve - needs to receive priority attention. After that the test requirements - incident radiation and diagnostics - follow naturally.

3.3.2.1 Excitations.

The range of parameters for excitations include the type of radiation, the spectrum and the time scale. Long term damage can usually be produced with a long-term steady-state radiation. Transient effects and short-term annealing require more intense, pulsed radiation sources. The effects of penetrating radiation in which the Z-dependence of absorption is not important can be produced by a wide range of radiation spectra. If photoelectric absorption is important, special attention is required to the spectrum. In this case there is usually a strong tradeoff between realism in absorption characteristics and available intensity.

This subject has received much attention as part of Simulation Fidelity investigations. The important point here is that the results of such investigations must be incorporated into recipes that can be routinely applied, and legally approved, to equipment hardness validation.

3.3.2.2 Diagnostics.

The diagnostics issues also are analogous to the EMP discussion. Detailed excitation and response diagnostics provide better information for comparison with analysis; functional diagnostics minimizes the system perturbation and generates directly applicable functional response conclusions. The rules by which these decisions are made need to be written down.

3.3.3 Tradeoffs.

The tradeoffs in choosing particular TREE validation methods have the same character as for EMP applications. More complex methods should be used only when the margin is insufficient to justify simple bounds. This should occur only when the extra costs of hardness validation, assurance, maintenance, and surveillance are preferable to the cost of incorporating a larger margin in the design.

3.3.4 Applications.

As in the EMP case, a lot of documents are needed to formalize the analysis and test methods to support the various validation options. These include standards for analyses and tests, specification formats for various levels of assembly from the elementary device up, and certified data/relations (e.g. generic worst case bounds on device response).

Sample partial drafts of two of the documents that are required are presented in Appendices B and C. These are not finished products, but only to illustrate the approach that can be taken.

APPENDIX A

DRAFT STANDARD STATISTICAL METHODS FOR HARDNESS VALIDATION ANAYLSIS

A.1 SCOPE.

The scope of this document is limited to the statistical tests required to categorize electronic piece parts.

A.1.1 OBJECTIVE.

A radiation hardened system is designed to survive a specific set of nuclear threats. This means that the response of individual piece parts to radiation environments must fall within certain well defined acceptance limits. Typically, the radiation environments can produce a number of damaging effects. In the hardness validation approach a methodology is developed for the analysis of piece part response to each potentially damaging effect. Each method imposes a design margin to cover uncertainties and inaccuracies. The uncertainties arise because of the wide variability characteristic of device radiation response. Consequently, statistical analysis plays a critical role in the definition and the quantitative assessment of design margins. Questions concerning the interrelationship of sample size, confidence level, failure probability, and the sample parameters can be quantitatively addressed using the statistical approach. In the past ambiguities, inconsistencies, and incompleteness have been associated with descriptions of statistical procedures applied to component categorization. The objective here is to describe the useful procedures as clearly and unambiguously as possible. Controversial questions and questions yet to be addressed will be identified.

A.1.2 DOCUMENT APPLICATION.

This document is applicable to neutron and total ionizing dose effects in all piece parts used in military systems. The environments of concern include: endo- and exo- atmospheric nuclear weapon environments, nuclear power sources, and natural space radiation environments.

Experimental data shows that temperature, circuit operating conditions, and simulation fidelity (the appropriateness of the radiation test facility for simulating the effect of interest) all play important roles in determining the response observed. An extensive literature exists which details the role of these factors in determining device response. The focus in the present document, however, is the relationship between survivability goals (survival probability and confidence level), sample characteristics (mean, standard deviation, and size), design margins, part categorization criteria, design margin breakpoints (demarcation levels), and test procedures for each part category (wafer level, lot level, relative frequency).

A.2 REFERENCED DOCUMENTS.

A.2.1 GOVERNMENT SPECIFICATIONS AND STANDARDS.

Unless otherwise specified, the following specifications and standards, in that issue of the Department of Defense Index of Specifications and Standards specified in the solicitation, form a part of this specification to the extent specified herein

SPECIFICATION

MILITARY

MIL-S-19500 - Semiconductor Devices, General Specification For
MIL-M-38510 - Microcircuits, General Specification For
MIL-C-45662 - Calibration System Requirements.

STANDARD

MIL-STD-202 - Test Methods For Electronics and
Electrical Component Parts.
MIL-STD-750 - Test Methods For Semiconductor Devices.
MIL-STD-883 - Test Methods And Procedures For
Microelectronics

Required copies of specifications and standards can be obtained from the contracting activity or as directed by the contracting officer.

A.3 DEFINITIONS.

A.3.1 DEFINITIONS. THE FOLLOWING DEFINITIONS APPLY:

A.3.1.1 Characterization test. The radiation characterization test consists of exposing the test parts to increasing total dose values until the radiation induced parameter value, PAR_R, for each part, passes the specified failure value.

A.3.1.2 Confidence Level. The probability P (usually given in percent) that at least a fraction, F, of the parts in the lot will survive.

A.3.1.3 Survivable Fraction. The proportion of the parts that survive which is obtained from the cumulative portion of the distribution below the failure level.

A.1.3.4 Part. The electronic part type used in a specific circuit application or test.

A.3.1.5 Parameter Value. The electrical parameter value measured for a device.

A.3.1.6 Lot. The collection of parts from which the sample has been taken.

A.3.1.7 Validation Test. The hardness validation testing of a sample of parts from a procurement lot.

A.3.1.8 Parameter Failure Value. The circuit failure value P of a particular parameter for the device under evaluation. This is generally determined by a worst case circuit analysis prior to radiation testing.

A.3.1.9 Parameter Specification Value. The device parameter specification value prior to irradiation.

A.3.1.10 Radiation Induced Parameter Value. The postirradiation parameter value PAR_R.

A.3.1.11 Measured Mean of the Logarithms of PAR_R. For the lognormal distribution where PAR_{Ri} is the parameter value measured for the ith device.

$$\ln(PAR_R) = 1/n \sum_{i=1}^{n} \ln\left(PAR_{Ri}\right)$$

A.3.1.12 Measured Standard Deviation of the Logarithms for PAR_R

$$s' = \left\{ 1/(n-1) \sum_{i=1}^{n} \left[\ln(PAR_{Ri}) - \ln(\overline{PAR})\right]^2 \right\}^{1/2}$$

A.3.1.13 One Sided Tolerance Limit. K_{TL} is calculated for a normal distribution. In the present statistical treatment of device response to radiation, it is assumed that the logarit m of the parameter values follow a normal distribution. For parameters that increase with radiation exposure, K_{TL} is a factor such that the probability is P, that at least a fraction F of the lot, will have parameter values less than the mean plus K_{TL} times the standard deviation. For parameters that decrease with radiation exposure, K_{TL} is a factor such that the probability is P, that at least a fraction F of the lot, will have parameter values greater than the mean minus K_{TL} times the standard deviation.

A.3.1.14 Parameter Design Margin. Note that the design margin is NOT defined in terms of the logarithm of the device parameter response but rather in terms of the nonlogarithmic parameter values. It is customary to approximate the mean of a lognormal distribution with the geometric mean given by exp $(\overline{\ln(PAR_R)})$.

$$PDM = PAR_F / \exp(\overline{\ln(PAR_R)})$$

For values that decrease with radiation

$$PDM = \exp(\overline{\ln(PAR_R)})/PAR_F$$

A.3.1.15 Total Exposure. The total ionizing dose or fluence will be designated X_F. For ionizing radiation the units are rads(Si), for neutrons the units are neutrons/cm^2.

A.3.1.16 Total Radiation Failure Value. X_F is the total exposure value for the part under test at which it fails.

A.3.1.17 Measured Logarithmic Mean of Exposure.

Let $Y_i = \ln(X_i)$ then

$$\bar{Y} = 1/n \sum_{i=1}^{n} Y_i$$

is the geometric mean which approximates the mean of a lognormal distribution.

A.3.1.18 Measure Logarithmic Standard Deviation of Exposure.

If $Y = \ln (X_F)$ then, for the lognormal distribution:

$$s(Y) = \left\{ (1/(n - 1)) \sum_{i=1}^{n} \left[Y_i - \bar{Y} \right]^2 \right\}^{1/2}$$

A.3.1.19 Part Categorization Criterion.

The PCC is defined to be

$$PCC = \exp[K_{TL}\ s(Y)]$$

As we shall see it is a measure of the degree to which the design margin is eroded by the dispersion of sample results and the uncertainty associated with a small sample.

A.3.1.20 Total Exposure Specification. The maximum exposure the part in question must survive is designated X_S.

A.3.1.21 Exposure Mean Failure Value. This is the measured logarithmic mean failure value which is approximated by the geometric mean·

$$\bar{X}_F = \exp(\bar{Y})$$

A.3.1.22 Total Exposure Design Margin.

$$TDM = X_F \;/\; X_S$$

A.4 VALIDATION METHODOLOGY - GENERAL.

Hardness validation for military systems with nuclear survivability requirements generally involves both analysis and experimental tests. In both cases the goal is to validate the design hardness by identifying the uncertainties involved and determining whether they have been appropriately accounted for. The uncertainties are allowed for in hardened designs by using piece parts with adequate design margins. The design margins employed incorporate a number of trade-offs of which the following are typical:

- Small design margins require realistic tests. The more realistic the test, the higher its cost. The cost is higher because fewer variations in test parameters are allowed.

- The simpler the tests and the greater the reliance on calculations, the greater the design margin required.

- The larger the design margin, the more costly the piece parts.

A.5 VALIDATION METHODOLOGY PROCEDURES.

A.5.1 THE VALIDATION PROCESS - DATA COLLECTION.

Before statistical calculations can be initiated three kinds of information must be acquired: radiation levels at the location of the part, past radiation response data on the devices, and the failure criteria to be applied.

A.5.1.1 Radiation Level at the Part. The radiation levels to which the piece part will be exposed in the system must be specified. These levels will not necessarily be the system levels because of shielding from the surrounding subsystems. A worst case estimate involves assuming the system levels apply (no shielding). The levels can usually be estimated approximately using simple analytic approximations. These should be used primarily to determine whether computer code calculations would be warranted and not as design guidelines. A wide range of codes are available for accurate estimates of radiation levels if their application is indicated.

A.5.1.2 Device Response Data. All past data should be considered. Since the design has already been accomplished we can assume that at least some data exists. The task will be to determine whether the quality and extent of the data is consistent with its application.

A.5.1.3 Failure Criteria. A worst case circuit analysis is required to establish the parameter value at which the piece part can be considered to have failed. In addition, it is necessary to decide upon the failure probability level that is tolerable. For worst case estimates it can be assumed that all devices in the system must operate properly and have the same maximum probability of failure. For example, if the system is to have a survival probability of 90% and contains 10^4 piece parts, the failure budget for each part would be 10^{-5}.

A.5.2 THE VALIDATION PROCESS - PART CATEGORIZATION.

The categorization of parts involves two basic elements:

- The determination of design margins for the parts.
- The specification of criteria for assigning the parts to categories on the basis of the design margins.

In addition, it is necessary to specify what category assignments signify with respect to testing and procurement.

A.5.2.1 Design Margins. In this document we advocate that only the design margin based upon fluence to failure be used. As previously defined this is given by

$$TDM = X_F/X_S$$

Where X_F is the geometric mean derived from the available data and X_S is the specification value after shielding effects have been accounted for. The geometric mean is calculated from the logarithmic mean of the observed device response in the samples tested.

$$X_F = \exp(\overline{Y})$$

where $$\overline{Y} = 1/n \sum_{i=1}^{n} Y_i$$

and $$Y = \ln(X_F)$$

A.5.2.2 Categorization Criteria. Two approaches to assigning criteria for categorizing parts have evolved: The design margin breakpoint method (DMBP), and the part categorization criterion method (PCC). Both of these involve taking account of the dispersion in part response. This is essential if the failure probability is to be kept within prescribed limits. The first applies to systems with moderate requirements where it is practical to assign a single criterion to all parts of the system. The second method applies to systems with more severe requirements where categorization criteria must be developed for each part type.

A.5.2.2.1 <u>Determination of the Part Categorization Criterion. This is done in three steps:</u>

- Determine the measured logarithmic standard deviation for the lot type of interest

  If $Y = \ln(X_F)$ then, for the lognormal distribution:

$$s(Y) = \left\{ (1/(n-1)) \sum_{i=1}^{n} \left[Y_i - \bar{Y} \right]^2 \right\}^{1/2}$$

- Determine the one sided tolerance limit from tabulated values for the confidence level and survival probability previously assigned.

- Calculate the PCC

$$PCC = \exp[K_{TL}\, s(Y)]$$

A.5.2.2.2 <u>Determination of the Design Margin Breakpoint. This can be done in three steps:</u>

- Estimate a worst case standard deviation for the part types involved.

- In this case we assume a large sample so that the one sided tolerance limit can be replaced with the number of standard deviations needed to achieve the survival level desired.

- Calculate the DMBP

$$DMBP = \exp[K_{TL}(Y)]$$

We see that the procedure in the two cases is essentially the same except that the values for DMBP will generally be larger than those for PCC.

A.5.2.3 Categories of Parts.

A.5.2.3.1 Category -1 Parts. There are several types in this category but the only one requiring statistical tests is the group designated CAT-1M. These parts are of marginal hardness and,therefore, require testing each time a lot is purchased or other special screening procedures. The presence of such parts imposes a considerable cost on the system. In these cases the design margin is less than PCC but greater than two.

A.5.2.3.2 Category -2 Parts. These parts do not require routine testing but may require occasional tests. In these cases the design margin (TDM) exceeds PCC.

A.5.2.3.3 Non-critical Parts. These parts have such large design margins that when compared to the categorization criteria they do not require testing.

A.5.2.3.4 Unacceptable Parts. These include parts with very low design margins. Parts with design margins less than one are always eliminated and those with values between one and two should be if alternatives are available.

APPENDIX B
DRAFT STANDARD METHOD FOR NEUTRON TRANSPORT CALCULATIONS

B.1 SCOPE.

This method describes computational techniques for transforming the environmental radiation levels specified for the system, to the reduced levels encountered at piece part locations within the system. It allows for intervening materials that may act as effective shields.

B.1.1 OBJECTIVE.

In certain applications a substantial amount of material may surround sensitive electronic piece parts. In such cases, neglect of the shielding effect of such material on the specified radiation levels could add unwarranted costs to the hardening process. A hierarchical approach to the problem is indicated. In this approach a series of analyses can be undertaken in which the design margins required decrease as the complexity of the analysis increases. This document outlines acceptable procedures for arriving at reduced environmental radiation levels by applying radiation transport analyses.

B.1.2 DOCUMENT APPLICATION.

This document is applicable to the calculation of shielding effects on all piece parts used in military systems. The environments of concern include nuclear weapons and nuclear power sources.

B.2 REFERENCED DOCUMENTS.

B.2.1 THE RADIATION SHIELDING INFORMATION CENTER (RSIC).

The Radiation Shielding Information Center is located at Oak Ridge National Laboratory, Post Office Box X, Oak Ridge, Tennessee 37831, operated by Martin Marietta Energy Systems, Inc. for the U.S. Department of Energy, telephone number 615- 674-6176. The Center collects, organizes, evaluates, and disseminates shielding information related to radiation from reactors, weapons, accelerators, and space radiations. Packages of computer codes and related information can be obtained from the center.

B.2.2 GENERAL REFERENCES.

Reactor Shielding for Nuclear Engineers, N.M. Schaeffer, Editor, Technical Information Center, Oak Ridge, TN (1973).

Engineering Compendium on Radiation Shielding, R.G. Jaeger et al., Springer-Verlag New York (1970).

B.3 PROCEDURES.

B.3.1 TRANSPORT CALCULATIONS - APPROXIMATE.

B.3.1.1 General.

It is useful to estimate the amount of neutron attenuation that might be encountered in a particular application without having to resort to extensive code calculations. For example, if the amount of attenuating material is so small that it makes a negligible difference in the fluence at the point of interest, then it would be wasteful to initiate a computer study. On the other hand, if significant reductions in fluence are indicated by exploratory calculations, and the accuracy of the calculations could have a marked effect on system survivability, then analysis using analytic or Monte Carlo methods is warranted.

B.3.1.2 Removal Cross Section Method.

In this method exponential attenuation is assumed. The removal cross section has been measured for many materials and is assumed energy independent. The rational here is that in a thick shield only the highest energy neutrons can penetrate a significant distance. For high energy neutrons the cross section is very close to the geometric cross section and therefore energy independent. Calculated values of removal cross sections are compared with measurements in Figure 1. The measured values are for: H, Li, Be, B, C, O, Al, Cl, Fe, Ni, Cu, W, Pb, Bi, and U (Ref. 1). Using an approach suggested by the results of Evans (Ref. 2) we show in Figure 1 the square root of the cross section plotted versus the cube root of the mass number. The agreement between the measured and calculated values is good except for hydrogen. The straight line is a plot of

$$\sigma^{1/2} = [2\,\pi]^{1/2}\,[\,R\,A^{1/3} + \lambda\,]$$

$R\,A^{1/3}$ has the characteristics of an effective nuclear radius (A is the mass number) and λ an effective "size" of the incident neutron. The values used to plot the line shown were 9×10^{-4} for R and 1.9×10^{-13} for λ. The above equation provides a convenient method for calculating removal cross sections for elements that have not been measured. Where hydrogen is involved a cross section of one barn should be used rather than a calculated value. The measured cross sections shown in Figure 1 are on the low side of values that have been reported.

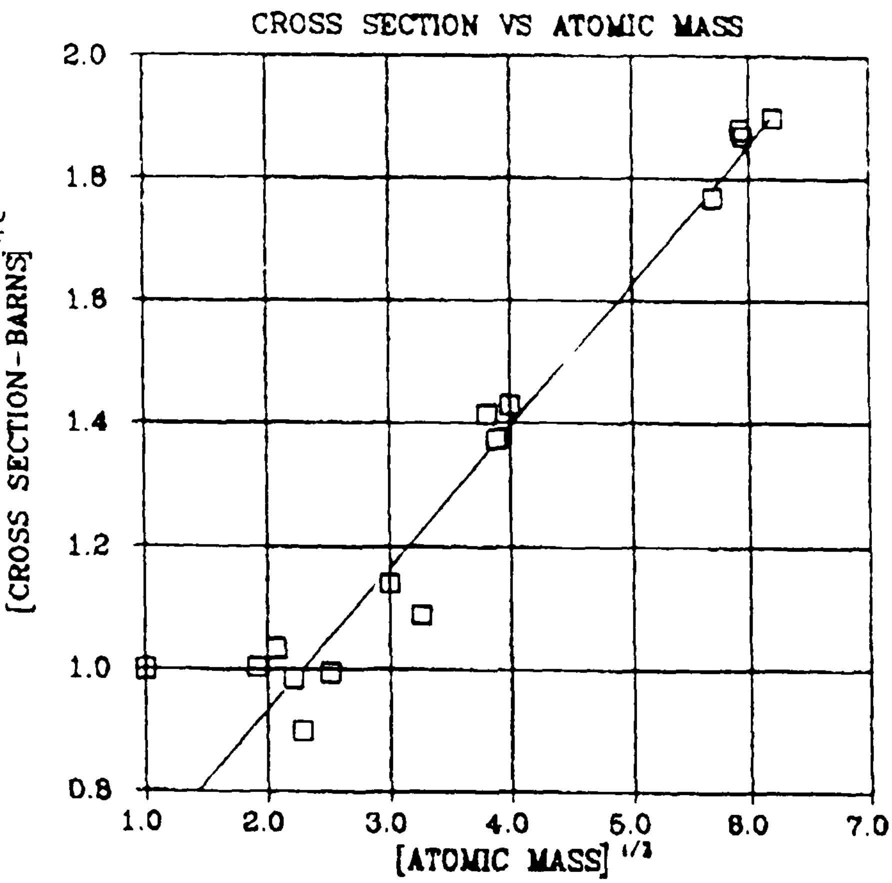

Figure 1. Experimental versus calculated removal cross sections.

B.3.1.3 Requirements.

The method strictly applies only to the attenuation by materials immersed in a hydrogenous medium where the point of interest is at least 10 centimeters from the shield. Under these circumstances it is found to give excellent agreement with experiment (Refs. 1, 3 - 5). If the hydrogenous material is not present, the use of removal cross sections does not give accurate results (Ref. 6). For example the measured result is a factor of 2 larger for a 10 cm slab of lead than that calculated.

B.3.2 TRANSPORT CALCULATIONS - EXACT.

B.3.2.1 General.

A general approach to the transport problem is to solve the Boltzman transport equation. Many methods of solution have been developed including: spherical harmonics, discrete ordinates, and the method of moments. In contrast to the approximate approach the accuracy of these methods is limited only by the labor invested in the computation. The discrete ordinates is widely used in applications at the present time. A brief description of this method follows.

B.3.2.2 Discrete Ordinates.

The discrete ordinates method is a numerical technique for solving the finite difference form of the Boltzman equation. It has been widely used in the form of the ONETRAN code which was developed at Los Alamos National Laboratory (Ref. 7), and in a new version called ONEDANT (Ref. 8). This code solves the multi-group Boltzman equations in one-dimensional (slab) geometry (Ref. 7). Early reviews of the method appear in (Refs. 9, 10).

B.3.2.3 Requirements.

The ONETRAN code will run on most large computers. The more recent ONEDANT has been run on the CDC 7600, CRAY 1, and the IBM/190. Extensive disk space can be required for large cross section libraries (e.g., ENDF/B-V).

B.3.3 MONTE CARLO METHODS.

B.3.3.1 General.

Monte Carlo Methods are a generally applicable approach to the transport problem. However, they can require long machine running times in that a large number of particle histories (10,000) must be run in order to obtain statistically significant results. Nevertheless, in many practical applications they provide the only realistic approach for obtaining accurate estimates (e.g., in 3D geometries). The MCNP code, described in the next section, is a popular state of the art code. A wide variety of variance reduction techniques have been applied in the code to insure efficiency of operation.

B.3.3.2 MCNP - Monte Carlo Neutron Photon Transport.

Solves transport problems for neutrons with energies in the 20 Mev to thermal range. It is a general-purpose, time dependent, generalized geometry (3D) computer code. It also treats photon transport problems (100 MeV to 1 keV) and coupled neutron-photon problems.

B.3.3.3 Requirements.

The program is designed to run on the following computers: CDC-7600, CYBER 176, CRAY 1, VAX, PRIME, and IBM 3033. Other machine version packages are available. Extensive disk space is needed for the large, cross section libraries that are supplied with the code (e.g., ENDF/B-V). The programming language used is FORTRAN 77.

B.4 LIST OF REFERENCES

1. H. Goldstein, Fundamental Aspects of Reactor Shielding, Addison-Wesley Publishing Company, Inc., (1959).

2. R.D. Evans, The Atomic Nucleus, McGraw Hill Book Company, Inc. (1955)

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4. B.T. Price, C.C. Horton, and K.T. Spinney, Radiation Shielding, Pergamon Press, (1957).

5. A.E. Profio, Radiation Shielding and Dosimetry, John Wiley & Sons, New York,(1979).

6. N.J. Rudie, Principles and Techniques of Radiation Hardening, Western Periodicals Company, CA (1976)

7. T.R. Hill, "ONETRAN: A Discrete Ordinates Finite Element Code for the Solution of the One-Dimensional Multigroup Transport Equation", LA-5990-MS, Los Alamos National Laboratory (1975).

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9. B.G. Carlson, "The Numerical Theory of Neutron Transport," in B. Adler, S. Fernback, and M. Rotenberg, Eds., Methods in Computational Physics, Vol. 1, Academic Press, New York, 1963.

10. F.R. Mynatt, "The Discrete Ordinates Method in Problems Involving Deep Penetrations," in A Review of the Discrete Ordinates S Method for Radiation Transport Calculations, Oak Ridge National Laboratory Report ORNL-RSIC-19, Oak Ridge, TN. (1968).

11. Los Alamos Radiation Transport Group, "MCNP--A General Monte Carlo Code for Neutron and Photon Transport, Version 2B," LA-7396-M, Revised (April 1981).

12. W. L. Thompson, E.D. Cashwell, T.N.K. Godfrey, R.G. Schrandt, O.L. Deutsch, and T.E. Booth, "The Status of Monte Carlo at Los Alamos," LA-8353-MS (May1980). (Also appears in ORNL/RSIC-44.)

APPENDIX C

STANDARD PRACTICES IN TREE CIRCUIT ANALYSIS

The purpose of this document is to establish a set of standard procedures to verify the actual hardness levels to which a circuit will not respond beyond an acceptable level.

The analysis will cover the following TREE environments.

1. Neutron Fluence
2. Ionization Rate
3. Long Term Ionization Dose (Total Dose)

The procedures to be followed in the Hardness Verification Analysis is:

1. Obtain circuit schematic and parts list

2. Obtain radiation test data for
   - 2.1 All discrete transistors
   - 2.2 All diodes
   - 2.3 All integrated circuits
   - 2.4 Other active parts
     - 2.4.1 Crystals
     - 2.4.2 Optical Isolators
     - 2.4.3 Fiber Optic Components
     - 2.4.4 Other semiconductor parts

3. Determine degraded parameter curves for all components listed above out to 10X specification level (to 100X when reasonable).

4. Perform a functional worst-case circuit analysis using accepted network analysis (hand or computer) techniques to verify that the circuit will perform correctly (within specification) when operated at worst-case temperature and radiation degraded device parameters (degraded from neutrons and total dose).

5. The analysis will be performed at the maximum design margin initially. If circuit performs within specification, then no further analysis is required. If the circuit does not perform within specification, then further analysis is required at the intermediate design margin. If the circuit performs within specification no further analysis is required but the piece-parts which contribute to the intermediate design margin must be hardness categorized.

6. The final analysis is performed at the base specification level when the circuit performance is not satisfactory at the intermediate level. If the circuit performance is satisfactory, then a separate hardness category is required of the piece-parts causing the circuit to have the design margin of one.

7. If the circuit performance is unsatisfactory at the base specification level, then the circuit requires redesign until a positive design margin is met.

8. The analysis is to be extended to consider the effects of the prompt ionization pulse. The analysis is to consider two conditions. One, the recovery time of the semiconductors (transistor, IC, diode) from the ionization pulse and the effect of the external circuit time constants on the circuit recovery time. (Transistor and diode recovery times can be calculated from the radiation pulse width and radiation storage time; analog IC recovery times will require test data; digital IC recovery times can be estimated from past data on similar devices.) The worst case recovery time or disturbance is then compared with the minimum time required to affect the system function. If the latter time is 10X the disturbance time, the circuit is rated uncategorized. If it is below 10X and above 3X then it is rated HCI-2. If it is between 3X and 1X then it is HCI-2. Below 1X indicates a redesign.

9. The final portion of the analysis considers permanent damage to the semiconductor devices form the prompt ionization pulse. The following procedure is to be used.

From pulsed ionization tests on the devices, or similar devices, an upper limit is placed on the amount of charge transferred across the semiconductor junction, Q_p, by a prompt ionization pulse whose intensity is 100X the specified environment level. This charge is multiplied by the maximum available voltage (e.g., power supply voltage) to place an upper bound on the amount of energy that can be deposited in the device. If this energy is less than 1 μJ the device is uncategorized. (An exception to the 1 μJ limit is microwave devices; for these use test data to determine safe limit.) If this limit is above the 1 μJ level, another upper bound on the energy that can be deposited in the device is calculated by using the value of the resistance in the circuit between the device and the power source,

R_c. That upper bound is $V_o^2 t_p / 4R_c$, where V_o is the power source voltage, R_c is the series resistance, and t_p is the pulse width of the response of the device to an ionization pulse (ionization pulse width plus storage time). If this value is below 1 μJ, the device is again uncategorized. If neither of these inequalities is satisfied, the smaller of the two energies is compared with experimental or model-generated data on the energy threshold for the device for electrical excitation. The device is then categorized as follows.

Relationship Between Calculated Damage Energy and Damage Threshold Energy	HCI Category
$W_{d1} > W_t$	Redesign Required
$W_{d1} < W_t < W_{d2}$	1M
$W_{d2} < W_t < 10^3 W_{d2}$	2

[A special analysis is required for transistors connected to transformers with a significant leakage inductance. Ionization-induced burnout has been observed during recovery from saturation because the inductive kick may overvolt the transistor. A simple analysis shows that this can only happen if the transistor is driven into hard saturation, for which the transition time during recovery is shorter than the saturation time. When this occurs, the peak voltage is estimated from the circuit inductance, transistor recovery time, and saturation current.]

Transient Ionization Effects Analysis

Transient ionization effects, that is, effects on the semiconductor electronics due to ionizing pulses which cause photocurrent flow, are divided into two categories, temporary, and permanent. Examples are upset (temporary) and ionization induced burnout or memory loss (permanent).

Temporary Effects

Analysis for temporary effects begins by establishing a "loss of function" time budget. It is necessary to know the length of time that the system is not required to function properly, yet the mission can be fulfilled. This budget may be established at the system level with the flowdown provided to the circuit or subfunctional level. If we are dealing with a subsystem or circuit, then the budget is established at these levels with additional flowdown budgets is required.

The budgets must establish an upper limit on system, subsystem, and circuit downtimes which is consistent with the requirements for system operation. The analyst begins to analyze at the circuit level using that budget.

In complicated systems, it may be very difficult to achieve the flowdown but a first cut should be attempted. As the circuit analysis progresses it may be necessary to adjust the budgets at the circuit level as well as the analysis progresses, but at some point the flowdown from the system levels is recalculated to reflect these adjustments.

Digital Microcircuits

It is possible from the data available, to make an upper limit estimate on the upset time of most digital microcircuits such as 54/74 series TTL, it is usually less than 5 μs but 10 μs can be used to provide an adequate safety margin. Typically, the upset level for these circuits is $>10^8$ rad/s (of course, bistable circuits are not included here, because they may return to either state following upset and must be reset, therefore the upset time depends on the time of arrival of the reset pulse). The availability of data should make this task straightforward.

The calculation of a series of digital circuits (for example, a set of gates) is obtained by determining the longest upset time in the string. More complex digital circuits than those mentioned above require test data (either from available test data or by performing actual test).

Linear Microcircuits

Linear microcircuits do not fall in any category of upset time. For example, the LM118 recovers in 35 μs and the LM111 recovers in excess of 150 μs when each are exposed to the same level of ionization pulse. Of course, most linear microcircuit recovery times are defined by the external circuit time constants. For example, feedback capacitance on op-amps and smoothing capacitors on voltage regulators contribute significantly to the microcircuit recovery time. This is to be considered in the analysis.

However, the analysis may be less complicated than one would think at this point. The analyst should calculate the longest time constant in a functional circuit that will dominate the recovery time.

NEUTRON ANALYSIS

The failure level for neutron effects is based on those semiconductor device parameters which are known to be sensitive to neutrons and which usually contribute to transistor functional performance. These parameters are listed in Table 1 for three functional categories. It is possible that other parameters may be important in some circumstances, for example h_{ie}. The analysts should be careful to include these in the analysis in addition to those listed.

Table 1. Usual parameters to be calculated for bipolar transistors.

For Switching Functions

min h_{FE}
max I_{CBO}
max V_{CESAT}

For Emitter Followers

min h_{FE}
max I_{CBO}
max V_{CESAT}
max V_{BE}

Amplifiers (AC or DC)

min h_{FE}
max I_{CBO}
max V_{CESAT}

1. The analysis begins by calculating the minimum (or maximum) values of the above parameters that are necessary for the circuit (or transistor stage) to perform to specifications.

When h_{FE} is the parameter under calculation, the following steps will be followed.

1. Calculate minimum current gain required for satisfactory circuit operation.

2. Determine the collector current at that point.

3. Using test results, plot $\Delta 1/h_{FE}$ vs neutron fluence, ϕ, (log/log) at the calculated current to determine the damage constant K at or slightly above the threat fluence. (Use mean values of $\Delta 1/h_{FE}$ for a given point, and obtain mean K.)

4. Using the current gain calculated in 1 above and the minimum published gain (at operating current and minimum spec temperature) calculate the $\Delta 1/h_{FE}$ allowable.

5. Using K, and $\Delta 1/h_{FE}$, calculate the fluence at which failure occurs.

6. If failure occurs at a neutron fluence equal to or below the threat fluence, Φ_T, then the circuit must be redesigned.

7. If failure occurs at a neutron fluence between Φ_T and $5\Phi_T$, the device is in hardness category HCI-1M.

8. If failure occurs at a neutron fluence between $5\Phi_T$ and $30\Phi_T$, then the device is categorized as HCI-2.

9. Failure above $30\Phi_T$ allows the device to be uncategorized.

10. The design margin is calculated as the ratio of the fluence at which failure occurs to the spec fluence.

For parameters other than h_{FE}, the following steps are to be followed.

1. Calculate the minimum (or maximum) value required for satisfactory circuit operation.

2. From test data determine the value of the parameter at 30X spec. If this value is satisfactory, then the device is uncategorized.

3. If unsatisfactory, determine the value at 5X spec. If this value is satisfactory, then the device is categorized as HCI-2.

4. If unsatisfactory, determine the value at 1X spec. If satisfactory, then the device is categorized as HCI-1M.

5. If unsatisfactory, then redesign is required.

6. The design margin is calculated by taking the ratio of the degraded (neutrons) value and the minimum (or max value).

Integrated circuits have a different set of parameters to consider for the analysis. These are listed in Table 2.

Table. 2. Usual parameters to be calculated for integrated circuits.

Digital ICs

Fanout or Sink Capability
Input Leakage Current
Maximum Clock Frequency (Propagation Delay Time)

Linear ICs

Open Loop Gain
Slew Rate
Input Offset Current
Input Offset Voltage

The analyst should note that there may be other parameters affected by neutrons that may contribute to circuit performance.

> [NOTE: For digital ICs, the parameters listed above are usually defined in the spec sheet over the military temperature range. In this case, it is not necessary to include the temperature effects in the analysis. For linear ICs, the opposite is true, the parameters listed above are specified at a given temperature and temperature effects are to be included in the analysis]

The analysis steps are as follows:

1. The circuit is analyzed to determine its function and the parameters critical to the performance of the function. It may be that the parameters in Table 2 do not enter into the calculation but they must be considered and evaluated.

2. The minimum (or maximum) values for the critical parameters are determined.

3. These values are compared with the radiation test data to determine acceptable circuit performance.

4. Values in step 2 above those at 30X spec render the IC uncategorized.

5. Values between 5X spec and 30X spec place the IC in Category HCI-2.

6. Values between 1X spec and 5X spec place the IC in Category HCI-1M.

7. Values below 1X spec require a redesign.

8. The design margin is the ratio of the degraded parameter to min (or max) required value.

This procedure is acceptable for digital ICs and for single stage linear ICs. However, for multistage linear circuits, employing several ICs in a string to perform a function, it is advantageous to consider the total circuit. For example, where several op-amps are used in a filter-amplifier combination. It may be that the overall gain remains satisfactory even though one amplifier's gain may be severely degraded. In this case, if that one amplifier were considered by itself it would be categorized as HCI-1M, yet when considered in the overall string, it is uncategorized.

Neutron specifications may include both a multiple burst scenario and an enhancement factor for rapid annealing phenomena. If the neutron rapid annealing enhancement factor has not been included, then the total neutron fluence of the largest single burst should be increased by a factor of 3 to account for rapid annealing.

NEUTRON RELATED DOCUMENTS

Military Standards

1. Method 1017.2, Neutron Irradiation, MIL-STD-883B, June 1982.
2. Method 1017, Neutron Irradiation, MIL-STD 750-C, May 1982.

DoD Adopted ASTM Standards

1. ASTM E263-77, Standard Method for Determining Fast-Neutron Flux by Radioactivation of Iron, June 1982.
2. ASTM E264-77, Standard Method for Determining Fast-Neutron Flux by Radioactivation of Nickel, June 1982.
3. ASTM E265-77, Standard Method For Determining Fast-Neutron Flux by Radioactivation of Sulfur, June 1982.
4. ASTM E720-80, Standard Guide For Selection of a Set of Neutron-Activation Foils For Determining Neutron Spectra Used in Radiation-Hardness Testing of Electronics, June 1982.
5. ASTM E721-80, Standard Method For Determining Neutron Every Spectra With Neutron Activation Foils For Radiation-Hardness Testing of Electronics, June 1982.
6. ASTM E722-80, Standard Practice For Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence For Radiation-Hardness Testing of Electronics, June 1982.

Hardness Assurance Reports

1. Piece Part Neutron Hardness Assurance Guidelies For Semiconductor Devices, DNA 5910F, 6 October 1981, A. Namenson, E. Wolick[illegible]. R. Berger, H. Eisen, J. Ferry, G. Messenger, R. Scace, Schafft.

2. Nuclear Hardness Assurance Guidelines For Systems With Moderate Requirements, AFWL-TR-76-147, September 1976.

Dosimetry Standards

1. ASTM E763-80, Standard Method For Calculation of Absorbed Dose From Neutron Irradiation by Application of Threshold-Foil Measurement Data.

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